

Article

Effects of Music Tempo Manipulation on Morning Neuromuscular Strength and Cognitive Performance in Males: A Standardised Approach

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Abstract

Background/Objectives: We investigated whether being exposed to preferred music (110–130 beats·min^{−1}) or music accelerated by 15%, played during morning exercise, influenced muscle strength and executive function assessed before and after exercise. **Methods:** Fourteen recreationally active males were recruited and completed seven sessions: (i) maximum (1RM) for bench press and back squat; (ii) three familiarisation sessions of strength and cognitive measures; (iii) three experimental conditions. Experimental trials were administered in a randomised counterbalanced design order of either preferred music at original tempo (MUS), preferred music accelerated by 15% (MUS15) during physical performance or no music (CON). On arrival, rectal and skin temperatures were measured alongside a battery of cognitive tests (trail making, Reys auditory verbal learning test, and Stroop word-colour interference test). Thereafter, isometric maximum voluntary contraction (MVC) with and without superimposed electrical stimulation was conducted and three repetitions were performed at 40, 60 and 80% of one repetition maximum (1RM) for bench press and back squat. Average force (AF), peak velocity (PV), time to peak velocity (tPV), and mean propulsive velocity (MPV) were recorded using MuscleLab linear encoders. The rate of perceived exertion and effort were asked after each set (RPE). **Results:** Music had no significant effect on MVC peak torque, % muscle activation, or key bench press and back squat outcomes. Most cognitive measures were unaffected, although time was perceived as faster during MVC ($p = 0.022$) on MUS. **Conclusions:** Music did not provide a significant acute ergogenic benefit for morning strength, power or cognitive function but may have modulated time perception.

Keywords: bench press; back squat; executive function; circadian rhythm; MVC; strength; music



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1. Introduction

Strength athletes may choose to train in the morning due to time constraints and to avoid crowded environments [1]. They are also often required to compete in the morning with many weightlifting, powerlifting and strongman competitions starting before 09:00 h (h) with even earlier weight-in times. However, human muscle power output and force production values are higher in the mid-afternoon or early evening regardless of the method used, the muscle groups tested or the mode and speed of contraction [2]. Cognitive performance can be equally essential for many athletes and has also been shown to be subjected to a time-of-day effect [3]. Considered as multifactorial, it includes many different components related to attention, accuracy, consistency, reaction time, vigilance, decision making and executive functions [4]. Executive functions notably include the ability to plan and coordinate considered action while updating it with inhibition processes of distractions to focus attention on the relevant information. Subjective mood states and motivation levels are worse in the morning than in the evening and are essential for tasks requiring higher cognitive function and skill [2].

Music has received increasing attention as a practical and low-cost intervention with the potential to acutely enhance physical and cognitive performance. However, its ergogenic effects do not seem to be equally distributed across all exercise modalities [5]. The evidence is generally strongest in cyclical, repetitive or rhythm-based tasks (such as walking, running or cycling), where performance can synchronise movement to an auditory beat [5–7]. In these contexts, music might not only act as a motivation stimulus but also as an external pacer, hence promoting auditory–motor synchronisation, improving movement consistency and economy, enhancing affect and reducing rate of perceived exertion (RPE) [6–8]. This might explain why music has often shown clearer benefits in rhythmic, endurance-based tasks, and increasingly in repetitive resistance exercise formats such as sets performed for multiple repetitions or to failure, than in singular maximal efforts where there is a smaller “window of opportunity” for ongoing entrainment [9–12]. Nonetheless, music may still benefit strength-based performance through other psychophysical pathways, including heightened arousal, increased motivation, improved attentional focus and greater readiness to exert maximal intent [8–13]. These are key determinants of force production and rapid neuromuscular output particularly relevant when examining outcomes such as maximal voluntary contraction, explosive force production and peak velocity [9,11,14].

In addition, the effects of music are likely moderated by its characteristics and context rather than presence alone [5,8,15]. Tempo or the speed at which a passage of music is or should be played (measured in beats per minute; bpm) appears to be particularly important, with faster or higher tempo music generally associated with larger performance benefits in exercise settings [5,16–18]. Loudness refers to the subjective perception of volume, whereas sound pressure level (SPL) measured in decibels (dB) is the objective physical measure of sound level and a fundamental aspect of musical intensity [15,17,19]. Together, these parameters play a crucial role in shaping the overall sound and the emotional impact may further increase motivation and arousal at least in some simple and gross motor tasks [15,20]. For example, higher intensity music, generally referring to tracks for which the tempo is higher than 120 bpm and SPL is ≥ 75 dB, has been shown to produce greater performance benefits when comparing against slower and quieter conditions (< 120 bpm and < 70 dB) [16,18]. However, the evidence on musical intensity remains mixed [15] and excessively loud exposures raise practical and auditory-health concerns [21–23].

Music may also enhance cognitive performance through its emotional impact on mood- and arousal-related mechanisms [20]. Music may also influence temporal cognition, that is, the perception and estimation of elapsed time during a task as well as attentional focus, particularly the direction of attention toward internal sensations or external task-relevant

cues [24,25]. In turn, this may alter how long efforts feel, which could affect perceived task duration, tolerance of exercise, and task enjoyment, as captured by instruments such as physical activity enjoyment scale (PACES) and potentially adherence to training sessions [5]. Preferred background music has been shown to increase task focus and reduce mind-wandering. Recent work has reported improvements in reaction time during vigilance and sport-specific tasks [26–29], as well as strength endurance [28].

Observation of the effects of listening to music to improve morning cognitive and strength and power performance may be obscured by lack of rigour and standardisation in the method employed. Intensity variables such as tempo, loudness, preference, timing of exposure and task characteristics should be treated as meaningful moderators that may determine whether any ergogenic or cognitive benefit is observed [5]. Many studies do not report control conditions versus different music speed, hence tempo effects, or familiarisation with the tests to be conducted [30]. Sample size is often not based on a power calculation and does not employ standardisation of participants' habitual music preferences that they consider motivational. Unlike other studies, we utilised a study design that incorporated two preferred music conditions, at original tempo and time-stretched by 15%. This approach ensured that any tempo-related effects were isolated. In addition, studies have often failed to control important factors such as chronotype, time of year, and time of day and to report participants' quality of sleep, which specifically relates to investigations of chronobiological nature and other considerations [30–32]. The main biases in individual studies come from “bias in measurement of the outcome” and “bias in selection of the reported result”, with a lack of well-controlled studies [33]. Recent systematic reviews highlight a rigorous approach that needs to be adopted by future investigations regarding measuring possible daily variations in human exercise performance [34,35].

Therefore, the aims of this study were to use a standardised protocol to investigate the effects of preferred music at its original tempo (MUS), the same music accelerated by 15% (MUS15), and a no-music control condition (CON) on morning (a) neuromuscular performance, with primary outcomes comprising isometric MVC peak torque with and without superimposed electrical stimulation, measured using a Biodex II dynamometer (Biodex. Corporation, Shirley, NY, USA), and bench press and back squat peak velocity (PV), measured using a MuscleLab linear encoder; (b) secondary cognitive outcomes assessed before and after the strength and power tasks, including measures of attention, memory and executive function; and (c) secondary perceptual and psychological outcomes, including perceived effort and exertion, felt arousal, affective valence, temporal cognition, enjoyment (PACES) and attentional focus. We hypothesised that preferred music at its original pace (MUS) would (i) acutely enhance strength measures with more pronounced effects in the bench press (BP) than the back squat (BS) and MVC compared to other conditions (MUS15 and CON), (ii) increase felt arousal, feeling scale and temporal cognition whilst reducing RPE and the acute impact of exercise in cognition, and (iii) improve cognitive performance assessed pre vs. post strength and power tasks.

2. Materials and Methods

2.1. Participants

Fourteen adults, all male in biological sex and gender and classified as “recreationally active” according to the “participant classification framework” [36], participated in the present study (Table 1). The participant cohort and control condition overlap with those reported in a companion investigation examining whole-body vibration; however, the present manuscript addresses separate experimental conditions and research questions [37]. All participants were recruited from the University Sport Science department student population.

Inclusion criteria were healthy adults aged 18–35 years, currently injury-free, with at least two years of weight/strength-training experience. Health and suitability for exercise were assessed using a pre-participation questionnaire and the Physical Activity Readiness Questionnaire (PAR-Q). Training experience was assessed through self-report during recruitment and assessment during 1RM testing. Participants were required to provide 20 music tracks that motivated them during gym exercise and to comply with the prescribed sleep schedule and pre-session exercise and caffeine restrictions. None received pharmacological treatment, including non-steroidal anti-inflammatory drugs (NSAIDs), throughout the study period. Habitual caffeine consumption was assessed using the caffeine consumption questionnaire (CCQ), and individuals consuming >150 mg/day were excluded [38]. All participants reported no preference for training at a particular time of day, and habitual training times were recorded using a two-week self-reported training diary. Recruiting participants with previous strength-training experience was intended to minimise the influence of early neural adaptations associated with strength gains in untrained individuals [39]. Exclusion criteria included depressed mood assessed using the Beck Depression Inventory [40], poor sleep quality indicated by a Pittsburgh Sleep Quality Index global score > 5 [41], and a diagnosed sleep disorder. Shift workers and individuals who had travelled outside the UK time zone within the month preceding testing were excluded. Additional exclusions were a muscle-related injury or broken/fractured bone within the preceding three years and risk factors and/or symptoms of cardiovascular disease identified during health screening. Only participants classified as intermediate chronotypes using the Composite Morningness Questionnaire [42] were eligible; those classified as morning or evening types were excluded.

Through interviews, it was established that the volunteers had minimal knowledge of the effects of time of day or time since sleep on human performance. Verbal explanation of the experimental procedure was provided to everyone; this included the aims of the study, the possible risks associated with participation and the experimental procedures to be utilised. Any questions were answered. Individuals then provided written, informed consent before participating in the study. Initial participant procedures, including pre-screening and familiarisation were conducted under BSc/MSc ethical approval granted by Liverpool John Moores University Research Ethics Committee on 4 November 2025 (251104LJMUSP-SREC54). Staff/PGR ethical approval was subsequently granted by the Liverpool John Moores University Research Ethics Committee on 25 November 2025 (251108LJMUREC75), while familiarisation was ongoing. Experimental sessions commenced on 28 November 2025 under this approval. The study was conducted in accordance with the Declaration of Helsinki. This study was registered retrospectively on [ClinicalTrials.gov](https://clinicaltrials.gov) (NCT07558408). The study protocol, eligibility criteria, intervention conditions, and primary and secondary outcome measures were defined prior to participant recruitment and were not modified following study commencement. No changes were made to the study design or outcomes after registration.

Table 1. Participants' physical characteristics, habitual daily intake and sleep from 7-day actimetry (mean $\pm$ standard deviation (SD) values). * Denotes recommended daily intake (RDI) values from the Nutrition Science Team [43]. **Bold** values indicate statistically significant differences between participants' mean daily intake and the recommended daily intake (RDI), assessed using one-sample *t*-tests.

Physical Characteristics	Mean $\pm$ SD
Age (years)	22.9 $\pm$ 3.7
Height (cm)	179.6 $\pm$ 9.2

Table 1. Cont.

Physical Characteristics	Mean $\pm$ SD	
Mass (kg)	87.1 $\pm$ 16.3	
Chronotype	34.9 $\pm$ 5.2	
Languid/vigorous	40.6 $\pm$ 6.1	
Flex/rigidity	46.5 $\pm$ 7.5	
Athletic level (1–5)	1.9 $\pm$ 0.5	
Habitual sleep onset time (decimal h)	23.1 $\pm$ 0.9	
1RM bench press (kg)	92.8 $\pm$ 26.0	
1RM back squat (kg)	124.3 $\pm$ 39.2	
Daily caffeine intake from questionnaire (mg)	110.0 $\pm$ 51.1	
Habitual daily intake	Participants intake	RDI *
Calories (kcal)	2109.7 $\pm$ 650.2	2500 ($p = 0.062$)
Fats (g)	164.9 $\pm$ 100.3	97 ($p = 0.039$)
Protein (g)	152.7 $\pm$ 40.5	55.5 ($p < 0.001$)
Carbohydrates (g)	115.8 $\pm$ 70.3	333 ($p < 0.001$)
Zinc (mg)	11.5 $\pm$ 4.7	9.5 ($p = 0.712$)
Magnesium (mg)	244.4 $\pm$ 69.0	300 ($p < 0.001$)
Vitamin B6 (mg)	3.2 $\pm$ 1.9	1.6 ($p = 0.006$)
Caffeine (mg)	24.3 $\pm$ 30.9	Not available
Water (ml)	3588.0 $\pm$ 1029.9	2000 ($p < 0.001$)
Habitual sleep		
Time in bed (decimal h)	8.0 $\pm$ 1.6	
Sleep efficiency (%)	85.1 $\pm$ 6.2	
Sleep latency (decimal h)	0.22 $\pm$ 0.23	
Fragmentation index (%)	24.9 $\pm$ 11.7	

Languid/vigorous describes susceptibility to drowsiness and lethargy following reduced sleep, with languid individuals (scores > 37) experiencing greater difficulty overcoming these effects. Flexibility/rigidity describes the adaptability of sleeping habits, including the ability to sleep at unusual times, with flexible individuals (scores < 37) having greater ability to adapt their sleep pattern and habits. Athletic level follows the participant classification framework [36]: 1 = recreationally active; 2 = trained/developmental; 3 = highly trained/national level; 4 = elite/international level; 5 = world class.

2.2. Research Design

All participants were required to visit the biomechanics laboratory (Liverpool, UK) on seven occasions (air temperature of 18.6–20.2 °C, globe temperature of 18.7–20.8 °C, 30.9–44.8% humidity, wet bulb globe temperature of 13.2–15.1 °C, barometric pressure of 978–1018 hPa and ambient light of 750 lux). Participants completed (i) one maximum repetition (1RM) for bench press and back squat and (ii) three familiarisation sessions of strength and cognitive performance tests one week prior to the experimental protocol. During familiarisations, participants completed a 7-day food diary that was analysed using Nutritics® analysis software (Education Edition, version 6.22, Ireland) by a Sport and Exercise Nutrition Register (SENR)-registered nutritionist and a 7-day habitual sleep recording using actigraphy (Motionwatch 8, CamnTech, Co., Dublin, Ireland), in addition to a sleep diary as a secondary measure. The remaining sessions consisted of (iii) three experimental sessions, all at least 72 h apart as a standardised recovery period. The experimental part comprised three experimental trials: (a) preferred music at original tempo (MUS), (b) preferred music time stretched by 15% (MUS15) and (c) no music (CON)] between 07:00 and 08:40 h (Figure 1). Participants retired the previous night around 22:30 h, woke up at 06:30 h and arrived at the laboratory around 07:00 h (± 15 min depending on allocation, see next section for clarification) in a fasted state (Figure 1). Participants were instructed to

avoid training or intense physical activity 48 h prior to any of the visits; otherwise, participants maintained their normal daily routines. Music was delivered during the MVC and weightlifting whilst resting through participant's own headphones in both music conditions. Sound pressure level was normalised for both track sets and played at ~75 dB to avoid practical and auditory-health concerns. Participants and testing researchers were blinded to whether MUS or MUS15 represented the original tempo condition, but they could not be blinded to music versus no music. The order of treatment was revealed at the end of the experiment by a researcher responsible for anonymisation and randomisation (J.P.S.A.).

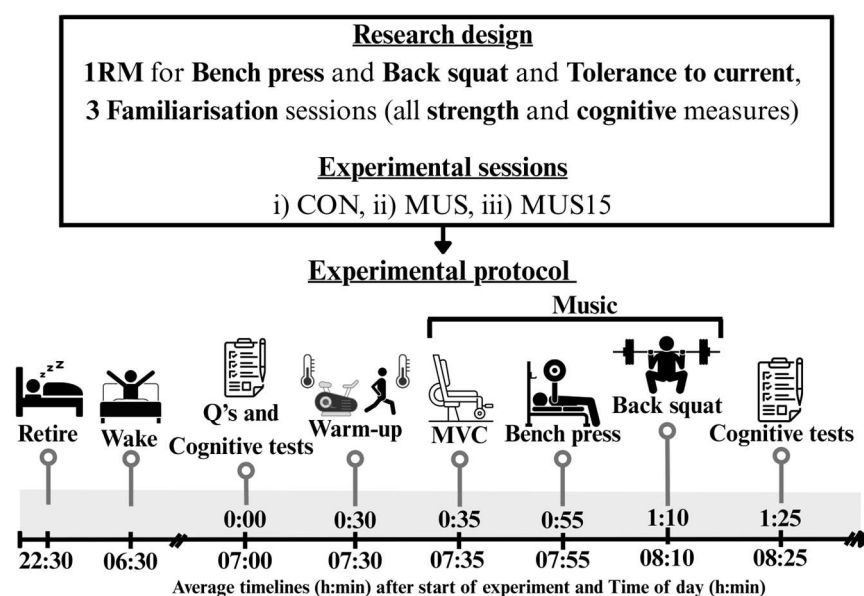


Figure 1. Schematic representation of the research design and experimental protocol undertaken by participants in the investigation. The thermometer represents rectal temperature (T_{rec}) and skin temperature (T_{sk}) measurements. Times shown represent the average start of each protocol segment rather than the exact timing of individual measurements. The cycling warm-up lasted five minutes; subsequent transition and preparation procedures are not displayed as separate segments.

All trials were performed with only one participant at a time, but with a staggered start so one participant came in at 06:45 h, the next at 07:00 h and the last for that morning's session at 07:15 h. This scheduling for participants was kept consistent for all sessions. All participants lived no more than 15 min away from the University laboratories. Participants were allocated to three groups (A, B and C) according to their ranked bench press and back squat 1RM values. Within each group, experimental condition sequences were assigned using a random-number generator, with the aim of distributing MUS, MUS15 and CON across the first, second and third experimental sessions. The incidence of the learning effect [44] was minimised by assigning the experimental conditions in counterbalanced order. Participants were not informed before each visit which condition they would undertake. The present study was carried out between the months of November to February 2025–2026 (UK autumn to winter), with morning sunlight exposure limited to <80 Lux before arriving at the laboratory. The sunrise–set range for the duration of the study was 07:12 to 08:03 h and 18:01 to 19:50 h.

2.3. Music Intervention

The music intervention was designed using a structured protocol informed by findings from previous experimental studies and reviews [5,6,8–11,16,18]. Existing research has examined music across multiple dimensions, including preferred versus non-preferred music, fast versus slow tempo, high versus low volume, self-selected versus researcher-selected

tracks, explicit versus censored content and genre differences. Based on this literature, the present intervention was developed based on modes of music selection and levels of intensity previously associated with beneficial effects on strength-endurance, maximal strength and affective responses. The following procedure was therefore implemented.

2.3.1. Selection

Participants were instructed to self-select twenty to twenty-five of their preferred, generally motivational tracks between the 1RM testing session and the second familiarisation session. The term “generally” was used to minimise mood-related bias during testing. Participants were free to select tracks of any genre, tempo or language. The only constraint present was the availability of each track on Spotify (Spotify AB, Version 1.2.81.x, Stockholm, Sweden). No exemplar tracks or playlists were provided to avoid influencing participants’ choice. The selected tracks were compiled into a playlist and submitted to the lead researcher before their second familiarisation session.

2.3.2. Screening

Once the playlist had been received, tracks were screened for bpm. Eligible tracks were required to fall between 110 and 130 beats·min⁻¹ (122 ± 4 bpm) and this was checked through Spotify’s “Mix” function which reveals each track’s official metrics. If insufficient tracks met this criterion to create a twenty-minute track set, participants were asked to provide an additional five preferred, generally motivational tracks to the playlist.

2.3.3. Audio Processing

Music tracks were downloaded as MP3 files and processed using Audacity (Audacity, version 3.7.5 for Windows 11, Muse, Cyprus). To ensure consistency across stimuli, each file was loudness-normalised and down-mixed from stereo to mono, thereby reducing variability associated with channel-dependent playback. These processed files served as the baseline stimuli. Modified stimuli were generated by applying a 15% increase in tempo using a pitch-preserving time-stretching procedure. This approach altered the temporal structure of the audio signal while preserving pitch and approximately maintaining higher-order spectral characteristics, including perceived timbral brightness (associated with the high-frequency energy of a sound making it bright, sharp or brilliant). Pilot testing was conducted across six tempo-modification conditions (5, 10, 15, 20, 25% and 30%). A 15% increase was selected as the optimal manipulation, representing the greatest temporal modification that remained sufficiently subtle and was not reliably identifiable original and modified tracks were presented on separate listening occasions. Following processing, MUS15 ranged between 127 and 150 bpm (141 ± 4 bpm), representing an average increase of 18 bpm relative to MUS (122 ± 4 bpm).

2.3.4. Blinding Measures

Participants and testing researchers were blinded to the identity of the two music conditions and to the nature of the tempo manipulation; however, blinding was not possible for comparison between the music and no-music conditions. MUS and MUS15 were labelled M1 and M2 and referred to as Music 1 and Music 2, respectively. The nature of the audio processing was not disclosed, so participants were not informed that the tempo had been manipulated. An empty audio segment was added to the end of MUS15 to match the duration of MUS and reduce the likelihood of identifying the manipulation from track set duration. Despite these measures, blinding between the two music conditions was only partially successful: nine of the fourteen participants reported being able to distinguish MUS from MUS15, and four of these correctly identified the nature of the manipulation.

Condition order was randomised and counterbalanced, with allocation concealed from participants and testing researchers until completion of data collection.

2.3.5. Timing of Delivery and Method

Music was delivered through the participants' own headphones to maintain their familiarity with the quality and depth of sound and introduced following the general warm-up, during MVC-specific warm-up and for the whole duration of the MVC protocol. The same headphones were used across both music interventions. Headphones were selected as the means of delivery due to their ability to target the auditory system directly compared to loudspeakers which may introduce low-frequency waves to the ambient, potentially producing mechanical resonance effects in musculoskeletal tissue. Music was then interrupted and re-introduced during the bench press-specific warm-up until the participant finished their back squats. The sound pressure level (SPL) was standardised at ~75 dB (A), as measured by a Digital Sound Level Meter (Tenma, model 72-13420, Tokyo, Japan). To ensure technical rigour, the device was set to A-weighting with a fast response time (125 ms), providing an accuracy of ± 3.5 dB across a measurement range of 40–130 dB.

2.3.6. Post-Session—Brunel Music Rating Inventory-2 (BMRI-2)

To ensure MUS was highly motivational and to understand how time-stretching may affect MUS15, participants were asked to complete the BMRI-2 [45] assessing each track set's characteristics. MUS scored 34.3 ± 7.5 arbitrary units (AU) and MUS15 scored 32.6 ± 7.3 AU, which were not significantly different ($p = 0.371$).

2.4. Protocol and Measurements: Familiarisation Sessions

The participants completed three familiarisation sessions of all the strength, cognitive and questionnaire measures, before being considered as ready to participate in the study. A coefficient of variation values less than or equal to 10% for variables between the second and third measures was used as criteria for familiarisation in alignment with the recommendations given by Atkinson and Nevill [46]. Familiarisation sessions took place at 09:30 h over a three-week period and finished one week before the study commenced to minimise learning effects. Participants arrived 0.5 h before the start of the test and rested in a seated position to minimise the influence of prior muscle activity. Participants completed each of the familiarisations in the following order: (i) cognitive battery of tests, consisting of trail-making test [47], Reys auditory verbal learning test (RAVLT) [48] and Stroop colour-word test [49,50], (ii) isometric maximal voluntary contraction (MVC) with and without percutaneous electrical stimulation, (iii) bench press and back squat loaded by 40, 60 and 80% of one repetition maximum (1RM).

2.5. Cognitive Battery of Tests

Cognitive performance was assessed before and after the exercise protocol using the trail-making test parts A and B, the Rey auditory verbal learning test and the Stroop colour-word test. Trail-making performance was quantified as completion time, RAVLT outcomes included total recall, intrusions and retention, and Stroop performance was assessed using total correct responses, errors and interference scores. Published reliability data indicate variable reliability for the trail-making test, particularly part B, good-to-excellent reliability for Stroop outcomes, and variable test-retest reliability across RAVLT measures [51,52]. All cognitive assessments were administered by the same trained assessor throughout the familiarisation and experimental sessions, using standardised instructions, administration procedures and scoring criteria, as detailed in Supplementary Methods S1.

2.6. Isometric Maximal Voluntary Contraction

Isometric quadriceps MVCs were performed for 3 s with and without superimposed electrical stimulation. Percutaneous stimulation was delivered using a constant-current stimulator (Digitimer DS7A, Hertfordshire, UK), with stimulus intensity established during familiarisation as 10% above that required to evoke the maximal resting twitch. Peak torque and voluntary activation were calculated using the interpolated twitch technique. Full electrode placement, stimulation and calculation procedures are provided in Supplementary Methods S2.

2.7. Bench Press and Back Squat

Participants performed three bench press and back squat repetitions at 40%, 60% and 80% 1RM, with 5 min recovery between efforts and instructions to complete the concentric phase with maximal intended velocity. Barbell displacement and velocity were measured using a MuscleLab linear encoder and MuscleLab Pro software (version 10.251.117.5396, Ergotest, Norway), operating at 200 Hz with a spatial resolution of 0.019 mm. The system has a reported peak velocity measurement error below 0.9%, high relative reliability ($r = 0.93$ – 0.97) and a coefficient of variation of approximately 2.3% [53]. Therefore, repetition producing the highest peak velocity and its associated mechanical variables was retained for analysis. Full exercise and outcome-definition procedures are provided in Supplementary Methods S3.

2.8. Perceptual and Psychological Outcomes

Affective valence, perceived arousal, attentional focus and enjoyment were assessed using the feeling scale [54], felt arousal scale [55], attentional-focus visual analogue scale [56] and an adapted PACES [57,58], respectively. Measures were administered before the warm-up, following MVC and following bench press and back squat. Full scale descriptions and scoring procedures are provided in Supplementary Methods S4.

2.9. Experimental Protocol and Temperature Measurements

Experimental sessions commenced one week after the final familiarisation session, with at least 72 h between conditions. On arrival at the laboratory, participants inserted a flexible rectal thermistor (Grant Instruments, Squirrel 2010 series, Shepreth, UK) approximately 10 cm beyond the external anal sphincter and then rested in a seated position for 30 min. Skin temperature was measured simultaneously using thermistors (Squirrel 2010 Series, Grant Instruments, Shepreth, UK) positioned on the left chest, forearm, thigh and calf. Resting rectal temperature (T_{rec}) and mean skin temperature (T_{sk}) were calculated from the average values recorded during the final 5 min of the seated-rest period. During this period, participants completed the Profile of Mood States questionnaire and subjective sleep questions. Subjective sleep information concerning the preceding night was collected before each experimental session to identify variation in sleep that could influence subsequent performance and inform interpretation of the findings. These measures characterised participants' pre-intervention status and were not outcomes of the exercise or music intervention. Participants subsequently completed a standardised 5 min warm-up at 150 W on a cycle ergometer (Corival CPET, Lode, Groningen, the Netherlands). Following the warm-up, the rectal probe was removed privately and the skin thermistors were detached. Participants then completed the MVC, bench press and back squat protocols in the standardised order described above. Full thermistor-placement procedures and equations used to calculate mean skin and mean body temperature are provided in Supplementary Methods S5.

2.10. Statistical Analysis

The primary outcomes in the present study were peak torque in the MVC and PV in the bench press and back squat. For MVC peak torque, sixteen participants were estimated to provide 80% statistical power ($p < 0.05$), with a diurnal variation effect size (ES) of 0.67 [3] for a one-tailed t -test. For PV for bench press, nine participants were estimated to provide 80% statistical power ($p < 0.05$), with a diurnal variation effect size (ES) of 0.92 [3] for a one-tailed t -test. For PV for back squat, nine participants were estimated to provide 80% statistical power ($p < 0.05$), with a diurnal variation effect size (ES) of 0.91 [3] for a one-tailed t -test. Diurnal effect sizes were used as a benchmark because the study aimed to investigate whether music could mitigate the morning reduction in neuromuscular performance. We recruited 20 participants to allow for a dropout, with $n = 6$ unable to complete the full protocol. The sample size estimation was performed using software G*Power 3.1 [59]. Data was analysed using the Statistical Package for Social Sciences version 30 (SPSS, Chicago, IL, USA). All data were checked for normality by creating three pairwise differences: MUS–MUS15, CON–MUS15 and MUS–CON. Normality plots were conducted with tests considering Shapiro–Wilk results as well as visually interpreting Q–Q plots and the presence of extreme outliers. In all cases, the normality of the difference scores was assessed using Q–Q plots and the Shapiro–Wilk test. In all cases, visual inspection indicated that the difference scores were approximately normally distributed, with no substantial outliers. General linear models were used to analyse all measurements collected; the significance of interactions and main effects were evaluated by analysis of variance (ANOVA). Sphericity violations were corrected by Greenhouse–Geisser ($\epsilon < 0.75$) or Huynh–Feldt ($\epsilon > 0.75$) and main effects by Bonferroni pairwise comparisons. All data is presented as means $\pm$ standard deviation (SD), unless otherwise stated. Significance was set at $p \leq 0.05$ [60]. Effect sizes are referred to as partial eta squared values (η^2_p) with values of 0.01, 0.06 and 0.14 corresponding to a small, medium and large effects, respectively [61]. Ninety-five percent confidence intervals (95% CI) and mean differences between pairwise comparisons are reported where suitable.

3. Results

3.1. Rest and Post Warm-Up Temperatures

There were no significant main effects of condition for T_{rec} , T_{sk} and mean body temperature (T_{mb}) ($p > 0.05$, Table 2). There was a main effect for “rest to post”, where T_{rec} increased, and T_{sk} and T_{mb} values decreased from rest to post warm-up, respectively (mean difference = $\uparrow 0.11$ °C CI = 0.06 to 0.15 °C, $p < 0.001$; mean difference = $\downarrow 0.59$ °C CI = 0.43 to 0.74 °C, $p < 0.001$ and mean difference = $\downarrow 0.15$ °C CI = 0.08 to 0.21 °C, $p < 0.001$). There were no significant interactions.

Table 2. Mean $\pm$ SD values and main effect for temperatures and all performance variables measured in this study in the three experimental conditions: CON, MUS and MUS15. p values and partial eta squared values (η^2_p) are given. **Bold** values denote $p < 0.050$.

Variable	CON	MUS	MUS15	Significance Condition (p , η^2_p)	Significance of Load/Pre–Post (p , η^2_p)	Interactions (p , η^2_p)
Pre–post cycle						
Rectal temperature (°C)	37.07 $\pm$ 0.31	36.92 $\pm$ 0.67	37.02 $\pm$ 0.43	$p = 0.600$, 0.03	$p < 0.001$, 0.65	$p = 0.468$, 0.05
Mean skin temperature (°C)	29.92 $\pm$ 0.41	30.06 $\pm$ 0.60	29.91 $\pm$ 0.62	$p = 0.477$, 0.05	$p < 0.001$, 0.82	$p = 0.284$, 0.09
Mean body temperature (°C)	34.45 $\pm$ 0.21	34.45 $\pm$ 0.39	34.46 $\pm$ 0.40	$p = 0.979$, 0.002	$p < 0.001$, 0.64	$p = 0.460$, 0.05
Heart rate (bpm)	103.7 $\pm$ 6.9	95.8 $\pm$ 6.8	104.7 $\pm$ 8.7	$p = 0.109$, 0.16	$p < 0.001$, 0.89	$p = 0.956$, 0.01
MVC						
Peak torque with stimulation (N·m)	259.0 $\pm$ 74.8	266.3 $\pm$ 79.0	260.5 $\pm$ 64.7	$p = 0.491$, 0.06		
% Muscle activation	96.3 $\pm$ 0.9	95.2 $\pm$ 2.3	96.7 $\pm$ 1.0	$p = 0.108$, 0.18		
RPE general (6–20)	18.4 $\pm$ 2.0	17.8 $\pm$ 2.4	17.4 $\pm$ 2.3	$p = 0.110$, 0.16		
RPE general (0–10)	9.3 $\pm$ 0.9	9.1 $\pm$ 1.3	8.8 $\pm$ 1.3	$p = 0.055$, 0.20		
Effort in task (1–10)	8.6 $\pm$ 1.7	8.4 $\pm$ 1.7	8.0 $\pm$ 2.0	$p = 0.139$, 0.15		
Peak torque without stimulation (N·m)	267.5 $\pm$ 77.7	273.1 $\pm$ 77.2	264.0 $\pm$ 69.6	$p = 0.220$, 0.11		
RPE general (6–20)	16.7 $\pm$ 2.6	17.3 $\pm$ 2.5	16.4 $\pm$ 3.0	$p = 0.075$, 0.18		
RPE general (0–10)	7.5 $\pm$ 1.3	7.6 $\pm$ 1.5	7.1 $\pm$ 1.8	$p = 0.495$, 0.05		
Effort in task (1–10)	8.7 $\pm$ 2.2	8.5 $\pm$ 2.3	8.2 $\pm$ 2.3	$p = 0.248$, 0.10		
Time passed total (decimal min)	16.9 $\pm$ 3.4	16.4 $\pm$ 3.3	16.6 $\pm$ 3.4	$p = 0.892$, 0.01	$p = 0.915$, 0.001	$p = 0.022$, 0.25
Time passed difference (decimal min)	0.59 $\pm$ 4.09	−2.22 $\pm$ 3.68	1.41 $\pm$ 3.96	$p = 0.022$, 0.25		
Felt arousal (1–6)	3.71 $\pm$ 1.44	3.79 $\pm$ 1.67	4.04 $\pm$ 1.67	$p = 0.553$, 0.04		
Feeling scale (−5 to +5)	1.86 $\pm$ 1.56	1.43 $\pm$ 2.21	1.64 $\pm$ 1.95	$p = 0.623$, 0.04		
Attentional focus (0–10)	5.21 $\pm$ 1.97	5.14 $\pm$ 2.18	5.71 $\pm$ 2.05	$p = 0.659$, 0.03		
PACES MVC (8–56)	34.7 $\pm$ 11.7	33.4 $\pm$ 13.2	35.4 $\pm$ 13.0	$p = 0.290$, 0.09		
Bench press						
Average power (W)	404 $\pm$ 106	404 $\pm$ 92	405 $\pm$ 97	$p = 0.973$, 0.001	$p < 0.001$, 0.64	$p = 0.503$, 0.06
Peak power (W)	686 $\pm$ 185	678 $\pm$ 178	684 $\pm$ 163	$p = 0.868$, 0.01	$p < 0.001$, 0.59	$p = 0.898$, 0.02
Time-to-peak power (s)	0.40 $\pm$ 0.17	0.43 $\pm$ 0.13	0.42 $\pm$ 0.15	$p = 0.641$, 0.03	$p < 0.001$, 0.49	$p = 0.460$, 0.05
Average force (N)	613 $\pm$ 174	613 $\pm$ 171	611 $\pm$ 172	$p = 0.853$, 0.01	$p < 0.001$, 0.93	$p = 0.339$, 0.08
Average velocity (m·s ^{−1})	0.72 $\pm$ 0.14	0.72 $\pm$ 0.13	0.73 $\pm$ 0.14	$p = 0.747$, 0.01	$p < 0.001$, 0.96	$p = 0.537$, 0.05
Peak velocity (m·s ^{−1})	1.11 $\pm$ 0.18	1.13 $\pm$ 0.20	1.14 $\pm$ 0.21	$p = 0.343$, 0.08	$p < 0.001$, 0.98	$p = 0.787$, 0.03

Table 2. Cont.

Variable	CON	MUS	MUS15	Significance Condition (p , η^2_p)	Significance of Load/Pre–Post (p , η^2_p)	Interactions (p , η^2_p)
Time-to-peak velocity (s)	0.46 ± 0.14	0.47 ± 0.11	0.48 ± 0.14	$p = 0.692, 0.03$	$p < 0.001, 0.59$	$p = 0.325, 0.08$
Displacement (cm)	43.6 ± 9.4	43.8 ± 8.9	44.1 ± 8.8	$p = 0.558, 0.03$	$p < 0.001, 0.74$	$p = 0.574, 0.05$
Mean propulsive velocity (m·s ^{−1})	0.75 ± 0.15	0.76 ± 0.14	0.77 ± 0.15	$p = 0.504, 0.05$	$p < 0.001, 0.97$	$p = 0.711, 0.03$
Rate of development of velocity (m·s ^{−2})	3.08 ± 1.14	2.98 ± 0.93	3.07 ± 0.94	$p = 0.745, 0.01$	$p < 0.001, 0.81$	$p = 0.137, 0.14$
RPE general (6–20)	12.1 ± 2.0	12.2 ± 2.6	12.1 ± 2.2	$p = 0.905, 0.01$	$p < 0.001, 0.90$	$p = 0.735, 0.03$
RPE general (0–10)	4.9 ± 1.3	5.1 ± 1.7	5.2 ± 1.6	$p = 0.611, 0.04$	$p < 0.001, 0.92$	$p = 0.539, 0.05$
Effort in task (1–10)	4.1 ± 1.5	4.0 ± 1.9	3.9 ± 1.7	$p = 0.801, 0.02$	$p < 0.001, 0.88$	$p = 0.706, 0.03$
Back squat						
Average power (W)	1130 ± 352	1130 ± 283	1123 ± 296	$p = 0.943, 0.003$	$p < 0.001, 0.77$	$p = 0.807, 0.022$
Peak power (W)	2616 ± 912	2699 ± 875	2670 ± 798	$p = 0.536, 0.05$	$p = 0.086, 0.20$	$p = 0.201, 0.14$
Time-to-peak power (s)	0.72 ± 0.16	0.73 ± 0.18	0.74 ± 0.17	$p = 0.713, 0.03$	$p < 0.001, 0.83$	$p = 0.736, 0.03$
Average force (N)	1641 ± 374	1635 ± 361	1632 ± 362	$p = 0.288, 0.09$	$p < 0.001, 0.91$	$p = 0.660, 0.04$
Average velocity (m·s ^{−1})	0.69 ± 0.08	0.70 ± 0.10	0.70 ± 0.11	$p = 0.788, 0.02$	$p < 0.001, 0.91$	$p = 0.598, 0.04$
Peak velocity (m·s ^{−1})	1.29 ± 0.21	1.32 ± 0.22	1.31 ± 0.20	$p = 0.553, 0.05$	$p < 0.001, 0.83$	$p = 0.191, 0.12$
Time-to-peak velocity (s)	0.76 ± 0.16	0.77 ± 0.18	0.78 ± 0.16	$p = 0.767, 0.02$	$p < 0.001, 0.84$	$p = 0.587, 0.04$
Displacement (cm)	63.1 ± 10.6	63.7 ± 9.3	64.2 ± 10.4	$p = 0.441, 0.05$	$p < 0.001, 0.66$	$p = 0.720, 0.04$
Mean propulsive velocity (m·s ^{−1})	0.72 ± 0.10	0.74 ± 0.11	0.73 ± 0.13	$p = 0.769, 0.02$	$p < 0.001, 0.91$	$p = 0.721, 0.03$
Rate of development of velocity (m·s ^{−2})	1.96 ± 0.57	2.02 ± 0.70	1.96 ± 0.52	$p = 0.603, 0.03$	$p < 0.001, 0.92$	$p = 0.362, 0.08$
RPE general (6–20)	13.1 ± 1.5	12.5 ± 1.9	13.0 ± 1.72	$p = 0.406, 0.06$	$p < 0.001, 0.84$	$p = 0.488, 0.05$
RPE general (0–10)	5.8 ± 0.4	5.9 ± 0.5	5.9 ± 0.4	$p = 0.795, 0.02$	$p < 0.001, 0.89$	$p = 0.547, 0.05$
Effort in task (1–10)	4.9 ± 1.6	4.6 ± 1.9	4.7 ± 2.1	$p = 0.487, 0.05$	$p < 0.001, 0.88$	$p = 0.885, 0.02$
Time passed—total (decimal min)	13.3 ± 5.0	13.6 ± 5.2	14.9 ± 4.6	$p = 0.291, 0.09$	$p = 0.334, 0.07$	$p = 0.395, 0.07$
Time passed—difference (decimal min)	0.47 ± 4.49	−0.01 ± 3.53	1.96 ± 5.18	$p = 0.408, 0.07$		
Felt arousal (1–6)	3.89 ± 1.30	3.93 ± 1.59	4.21 ± 1.63	$p = 0.232, 0.11$		
Feeling scale (−5 to +5)	2.14 ± 1.23	2.29 ± 1.77	2.07 ± 1.64	$p = 0.865, 0.01$		
Attentional focus (0–10)	5.43 ± 2.10	5.29 ± 2.16	4.89 ± 2.50	$p = 0.525, 0.05$		
PACES lifts (8–56)	44.1 ± 8.3	43.4 ± 8.9	45.4 ± 8.6	$p = 0.320, 0.08$		

3.2. MVC Peak Torque and % Muscle Activation

There were no significant main effects for condition for isometric MVC peak torque with or without stimulation or % muscle activation, where post hoc comparisons with stimulation showed the MUS condition peak torque not to be significantly different from the CON and MUS15 values (mean difference = $\uparrow 7.3$ N·m, CI = -7.9 to 22.5 N·m, $p = 0.634$ and $\uparrow 5.8$ N·m, CI = -15.0 to 26.7 N·m, $p = 1.000$ see Figure 2 and Table 2). Without stimulation, the MUS condition was not significantly different to CON and MUS15 ($\uparrow 5.5$ N·m, CI = -4.8 to 15.8 N·m, $p = 0.496$ and $\uparrow 9.1$ N·m, CI = -5.9 to 24.1 N·m, $p = 0.360$). The % muscle activation in MUS was not significantly different from those of CON and MUS15 ($\downarrow 1.0\%$, CI = -3.0 to 0.8% , $p = 0.406$ and $\downarrow 1.5\%$, CI = -3.5 to 0.5% , $p = 0.178$). No significant effect of condition was found in RPE immediately after MVC with or without stimulation, although numerically different values were found for RPE effort after MVC with stimulation, where RPE values were higher in the CON than MUS and MUS15 conditions (9.3, 9.1 and 8.8 AU, respectively) and RPE general values after MVC without stimulation. Post hoc analysis showed no difference in RPE effort values for MUS15 and MUS ($p = 0.088$) or CON and MUS or MUS15 ($p = 0.577$ and 1.000). There was a significant main effect for condition for time passed during MVC for faster time during MUS compared to CON and MUS15. No other variables showed significance.

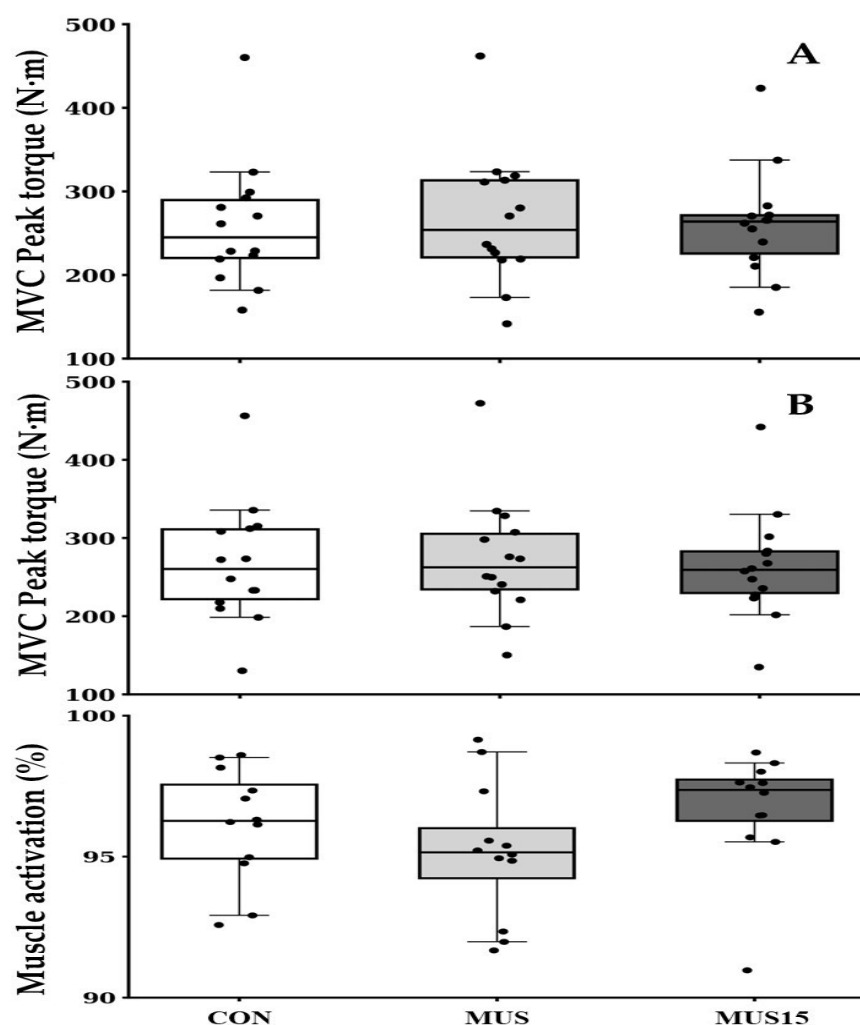


Figure 2. Individual and median ($\pm 95\%$ CI) values of isometric MVC peak torque with (A) and without stimulation (B) and % muscle activation for the three experimental conditions (CON, MUS and MUS15).

3.3. Bench Press

There was no significant main effect of condition on the primary bench press outcome, peak velocity (PV; $p = 0.343$, $\eta^2_p = 0.08$), with no significant differences between MUS and CON or MUS15 (mean difference = $\uparrow 0.02 \text{ m}\cdot\text{s}^{-1}$, 95% CI = -0.04 to $0.07 \text{ m}\cdot\text{s}^{-1}$, $p = 1.000$; and $\downarrow 0.01 \text{ m}\cdot\text{s}^{-1}$, 95% CI = -0.06 to $0.03 \text{ m}\cdot\text{s}^{-1}$, $p = 1.000$, respectively; Figure 3 and Table 2). Likewise, no significant main effects of condition were observed for the secondary bench press mechanical or ratings of perceived exertion and effort (all $p > 0.05$). As expected, there was a main effect of “load” for all bench press variables measured. For average power (AP), peak power (PP), average velocity (AV), peak velocity (PV), displacement (D), mean propulsive velocity (MPV) and rate of development of velocity (RDV), values were highest at 40% of 1RM and lowest at 80% of 1RM ($\uparrow 113.6 \text{ W}$, $\uparrow 179.0 \text{ W}$, $\uparrow 0.56 \text{ m}\cdot\text{s}^{-1}$, $\uparrow 0.89 \text{ m}\cdot\text{s}^{-1}$, $\uparrow 5.58 \text{ cm}$, $\uparrow 0.63 \text{ m}\cdot\text{s}^{-1}$ and $\uparrow 3.32 \text{ m}\cdot\text{s}^{-2}$, respectively), whereas time to PP (tPP), average force (AF) and time to PV (tPV) were significantly lowest at 40% of 1RM and highest at 80% of 1RM ($\downarrow 0.28 \text{ s}$, $\downarrow 323.2 \text{ N}$ and $\downarrow 0.30 \text{ s}$, respectively). In a similar fashion, there was a corresponding significant main effect for load on RPE general, effort and effort in task. Lower values were found at 40% of 1RM and highest at 80% of 1RM ($\downarrow 5.9$, $\downarrow 3.9$ and $\downarrow 4.2 \text{ AU}$, respectively). There was no significant interaction between “condition” and “load” for any variables.

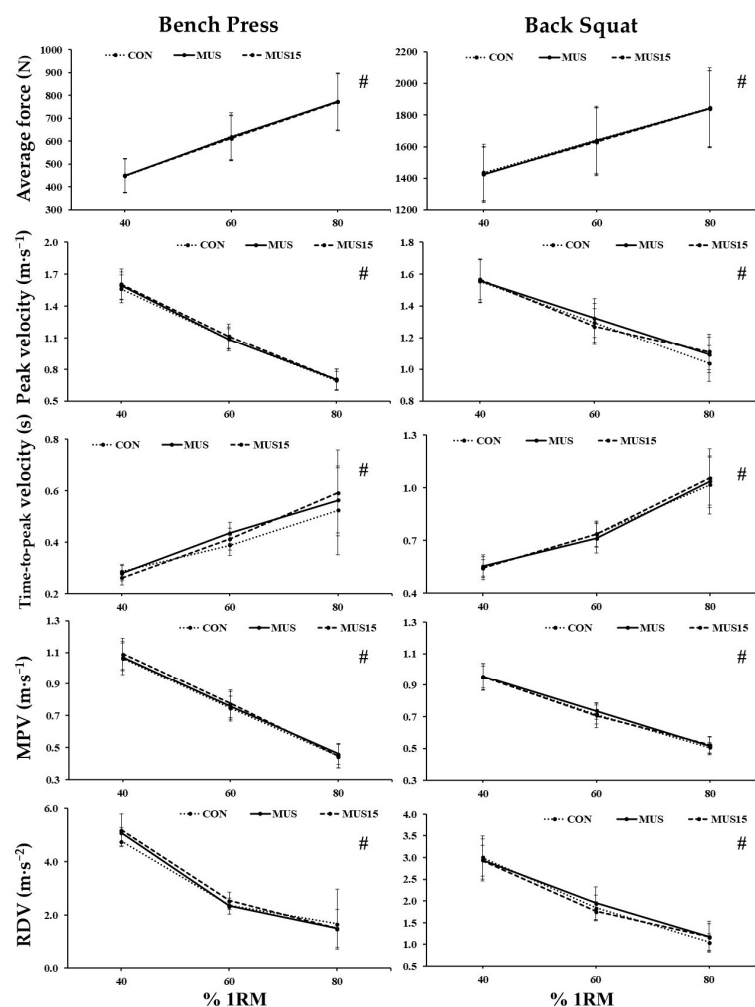


Figure 3. Mean and 95% CI values of each performance variable for morning (07:30 h) bench press and back squat at 40, 60 and 80% 1RM loads for the three experimental conditions (CON, MUS and MUS15). # denotes main effect for load as shown by Bonferroni pairwise comparisons ($p < 0.05$). RDV and MPV denote rate of development of velocity and mean propulsive velocity, respectively.

3.4. Back Squat

There was no significant main effect of condition on the primary back squat outcome, PV ($p = 0.553$, $\eta^2_p = 0.05$), with no significant differences between MUS and CON or MUS15 (mean difference = $\uparrow 0.03 \text{ m}\cdot\text{s}^{-1}$, 95% CI = -0.04 to $0.10 \text{ m}\cdot\text{s}^{-1}$, $p = 0.900$; and $\uparrow 0.01 \text{ m}\cdot\text{s}^{-1}$, 95% CI = -0.07 to $0.09 \text{ m}\cdot\text{s}^{-1}$, $p = 1.000$, respectively). Likewise, no significant main effects of condition were observed for the secondary back squat mechanical or ratings of perceived exertion and effort (all $p > 0.05$). As expected, there was a main effect of “load” for all back squat variables measured. For AP, AV, PV, D, MPV and RDV, values were highest at 40% of 1RM and lowest at 80% of 1RM (mean difference = $\uparrow 365.5 \text{ W}$, $\uparrow 0.39 \text{ m}\cdot\text{s}^{-1}$, $\uparrow 0.48 \text{ m}\cdot\text{s}^{-1}$, $\uparrow 6.23 \text{ cm}$, $\uparrow 0.44 \text{ m}\cdot\text{s}^{-1}$ and $\uparrow 1.82 \text{ m}\cdot\text{s}^{-2}$, respectively), whereas tPP, AF and tPV were significantly lowest at 40% of 1RM and highest at 80% of 1RM (mean difference = $\downarrow 0.49 \text{ s}$, $\downarrow 413.28 \text{ N}$ and $\downarrow 0.44 \text{ s}$, respectively). There was a corresponding significant main effect for load on RPE general, effort and effort in task. Lower values were found at 40% of 1RM and highest at 80% of 1RM (mean difference = $\downarrow 6.0$, $\downarrow 3.8$ and $\downarrow 4.3 \text{ AU}$, respectively). A trend effect of “load” was found for PP, highest at 40% of 1RM and lowest at 80% of 1RM (mean difference = $\uparrow 282.4 \text{ W}$). There was no significant interaction between “condition” and “load” for any back squat variables.

3.5. Feeling Scale, Felt Arousal Scale and Attentional Focus

There was no significant effect of condition for feeling scale, felt arousal scale and attentional focus by session nor per section (pre, MVC and bench press and back squat, Table 2).

3.6. Cognitive Function Tests

3.6.1. Trail Making

There were no significant main effects of condition on trail-making A or B values, although there was a significant main effect of “time” for trail-making A, where time to completion was longer post-exercise compared to pre-exercise (mean difference = $\uparrow 1.24 \text{ s}$, $p = 0.012$; Table 3). There was no significant interaction between “condition” and “time” for any trail-making variables.

Table 3. Mean $\pm$ SD values for assessments of the trail-making test (parts A and B), Rey auditory verbal learning test (RAVLT) and Stroop task in the CON, MUS and MUS15 conditions. These values represent scores averaged across the two assessment time points, not pre-to-post differences. Main effects of condition and time and condition $\times$ time interactions are reported using p -values and partial eta squared (η^2_p). **Bold** values denote $p < 0.050$.

Variable	CON	MUS	MUS15	Significance Condition (p , η^2_p)	Significance of Pre-Post (p , η^2_p)	Interactions (p , η^2_p)
Cognitive tests						
Trail-making test A (s)	12.2 $\pm$ 3.7	13.0 $\pm$ 6.1	11.9 $\pm$ 3.9	$p = 0.415$, 0.06	$p = 0.012$, 0.39	$p = 0.399$, 0.06
Trail-making test B (s)	28.5 $\pm$ 14.8	29.6 $\pm$ 18.1	34.1 $\pm$ 20.2	$p = 0.277$, 0.09	$p = 0.299$, 0.08	$p = 0.257$, 0.10
RAVLT—Total numbers	51.4 $\pm$ 15.6	49.4 $\pm$ 15.3	48.3 $\pm$ 17.4	$p = 0.427$, 0.06	$p = 0.315$, 0.08	$p = 0.373$, 0.07
RAVLT—Distractions	5.5 $\pm$ 2.1	6.2 $\pm$ 1.9	5.6 $\pm$ 1.8	$p = 0.198$, 0.12	$p = 0.271$, 0.09	$p = 0.187$, 0.12
RAVLT—Retention	10.7 $\pm$ 3.7	10.1 $\pm$ 3.9	10.5 $\pm$ 3.7	$p = 0.701$, 0.03	$p = 0.068$, 0.23	$p = 0.298$, 0.09

Table 3. Cont.

Variable	CON	MUS	MUS15	Significance Condition (p , η^2_p)	Significance of Pre–Post (p , η^2_p)	Interactions (p , η^2_p)
Stroop						
Colours—total	92.1 ± 19.7	92.9 ± 16.9	90.4 ± 17.2	$p = 0.374$, 0.07	$p = 0.398$, 0.06	$p = 0.823$, 0.01
Colours—error	0.1 ± 0.3	0.0 ± 0.1	0.0 ± 0.0	$p = 0.307$, 0.08	$p = 0.104$, 0.19	$p = 0.307$, 0.08
Colours not words—total	67.0 ± 13.1	66.0 ± 12.4	64.6 ± 8.2	$p = 0.603$, 0.04	$p = 0.161$, 0.15	$p = 0.121$, 0.16
Colours not words—error	0.1 ± 0.3	0.3 ± 0.7	0.0 ± 0.1	$p = 0.049$, 0.21	$p = 0.671$, 0.01	$p = 0.241$, 0.11
Colours interference	15.6 ± 7.3	16.9 ± 7.2	16.1 ± 6.3	$p = 0.774$, 0.02	$p = 0.433$, 0.05	$p = 0.155$, 0.14
Words—total	140.5 ± 21.6	142.3 ± 23.9	139.0 ± 23.5	$p = 0.434$, 0.06	$p = 0.008$, 0.43	$p = 0.423$, 0.06
Words—error	0.1 ± 0.3	0.1 ± 0.4	0.0 ± 0.1	$p = 0.458$, 0.05	$p = 1.000$, 0.00	$p = 0.337$, 0.08
Words not colours—total	125.6 ± 24.8	127.2 ± 26.1	127.6 ± 24.9	$p = 0.825$, 0.02	$p = 0.002$, 0.53	$p = 0.005$, 0.34
Words not colours—error	0.0 ± 0.1	0.2 ± 0.5	0.0 ± 0.1	$p = 0.291$, 0.09	$p = 0.266$, 0.09	$p = 0.140$, 0.15
Words interference	5.9 ± 5.6	5.9 ± 6.3	4.6 ± 3.6	$p = 0.587$, 0.04	$p = 0.210$, 0.12	$p = 0.032$, 0.24

3.6.2. Rey Auditory Verbal Learning Test

There were no significant main effects of condition on total numbers, distractions or retention. A trend effect of “time” for retention was observed, where retention was highest pre-exercise compared to post (mean difference = $\uparrow 0.35$, $p = 0.068$). There was no significant interaction between “condition” and “time” for any RAVLT variables.

3.6.3. Stroop

A main effect for condition was observed for colours not word (CW) error values ($p = 0.049$). But post hoc comparison revealed no significance between MUS and MUS15 (0.3 ± 0.7 and 0.0 ± 0.1 AU, respectively, $p = 0.086$). No effect was found between CON and MUS or MUS15. There was a significant effect of “time” on words (W) and words not colour (WC) total values, where pre-to-post values were highest for MUS15 and lowest for MUS on both variables (mean difference = $\uparrow 2.4$ AU, $p = 0.008$ and $\uparrow 6.9$ AU, $p = 0.002$, respectively). There was a significant interaction of “condition” and “time” for WC total, indicating that the pre–post change differed across conditions. WC total increased in CON ($\uparrow 9.2$ AU) and MUS15 ($\uparrow 16.2$ AU) but decreased slightly in MUS ($\downarrow 1.5$ AU), with better performance described as a higher total. Words interference followed a similar pattern ($p = 0.032$). MUS15 had the biggest improvement pre–post ($\downarrow 2.5$ AU), followed by improvements in CON ($\downarrow 1.7$ AU) and a worse score post for MUS ($\uparrow 2.5$ AU); a lower interference score is linked to better performance.

3.7. Resting Profile of Mood States, Caffeine Withdrawal and Sleep Questionnaires

There was a significant effect of alertness ($p = 0.038$) and calmness ($p = 0.036$) (see Table 4). Pairwise comparisons showed significantly lower resting alertness in CON, compared to MUS but not MUS15 (mean difference = $\downarrow 1.14$ AU, 95% CI = -2.21 to -0.07 AU, $p = 0.035$; and $\downarrow 1.21$ AU, 95% CI = -2.66 to 0.23 AU, $p = 0.114$, respectively), alongside significantly higher resting calmness in MUS15, compared to MUS but not CON (mean difference = $\uparrow 2.14$ AU, 95% CI = 0.93 to 3.36 AU, $p = 0.001$; and $\uparrow 1.79$ AU, 95% CI = -0.45 to 4.02 AU, $p = 0.141$, respectively). No significant effect of condition was observed for other mood profiles (anger, confusion, depression, fatigue or happiness), nor caffeine withdrawal symptoms or sleep questionnaires.

Table 4. Mean $\pm$ SD values and main effects for sleep questions, tiredness and alertness, profile of mood states (POMS) and caffeine withdrawal symptom scores for three conditions: CON, MUS and MUS15. p values and partial eta squared values (η^2_p) are given. **Bold** values denote $p < 0.050$.

Variable	CON	MUS	MUS15	Significance Condition (p , η^2_p)
Sleep questionnaires				
Fall asleep	-0.4 ± 2.8	0.6 ± 3.0	1.1 ± 2.9	$p = 0.374$, 0.07
Get to sleep	-0.3 ± 2.3	-1.3 ± 2.7	-1.0 ± 2.8	$p = 0.451$, 0.05
Well slept	0.8 ± 2.2	0.1 ± 1.9	1.4 ± 1.9	$p = 0.162$, 0.13
Waking time	-1.9 ± 2.4	-2.1 ± 1.7	-2.0 ± 2.3	$p = 0.955$, 0.004
Alertness after waking	-0.9 ± 2.2	-0.6 ± 2.7	0.3 ± 2.0	$p = 0.392$, 0.07
Stanford Questionnaire	3.2 ± 0.9	2.7 ± 0.7	2.6 ± 0.8	$p = 0.084$, 0.18
Tiredness (0–10)	5.2 ± 1.9	4.4 ± 1.8	4.1 ± 1.7	$p = 0.145$, 0.14
Alertness (0–10)	4.1 ± 1.8	5.2 ± 1.6	5.3 ± 2.1	$p = 0.038$, 0.22
POMS				
Vigour	6.3 ± 3.0	6.4 ± 3.5	7.4 ± 3.4	$p = 0.196$, 0.12
Anger	2.0 ± 4.3	1.5 ± 1.9	0.9 ± 1.7	$p = 0.426$, 0.05
Tension	0.8 ± 1.2	0.7 ± 1.2	0.4 ± 0.9	$p = 0.546$, 0.04
Calm	7.1 ± 2.6	6.8 ± 2.6	8.9 ± 2.6	$p = 0.036$, 0.26
Happiness	6.1 ± 2.7	6.6 ± 2.8	7.1 ± 3.1	$p = 0.369$, 0.07
Confusion	2.4 ± 3.2	1.9 ± 1.8	0.9 ± 1.4	$p = 0.143$, 0.14
Depression	1.4 ± 2.9	1.1 ± 1.5	0.6 ± 0.9	$p = 0.352$, 0.07
Fatigue	5.1 ± 3.3	4.8 ± 3.8	3.7 ± 3.2	$p = 0.362$, 0.07
Caffeine withdrawal symptoms	25.6 ± 6.7	26.9 ± 10.0	23.4 ± 6.8	$p = 0.341$, 0.08
Felt arousal (1–6)	2.4 ± 1.2	2.9 ± 1.2	2.7 ± 1.2	$p = 0.360$, 0.08
Feeling scale (–5 to +5)	0.6 ± 2.1	1.4 ± 1.7	1.4 ± 1.9	$p = 0.210$, 0.11
PACES general (8–56)	49.1 ± 8.2	48.3 ± 8.3	46.7 ± 10.3	$p = 0.557$, 0.03
BMRI-2 (0–42)	NA	34.3 ± 7.5	32.6 ± 7.3	$p = 0.371$, 0.06

4. Discussion

We found in recreationally active males tested under standardised morning conditions that preferred music at its original tempo or accelerated by 15% had no significant effect on the primary outcomes of isometric MVC peak torque, measured with and without superimposed electrical stimulation, or bench press and back squat peak velocity at 40, 60 and 80% of 1RM. No significant effects of condition were observed for the secondary neuromuscular outcomes, including voluntary activation, mean propulsive velocity, time-to-peak velocity and average velocity. These findings contrast with those of a recent meta-analysis reporting ergogenic effects of music on physical performance [5,16,62]. Our results do not support our first hypothesis, following a standardised protocol that incorporated some of the main concerns in the literature regarding chronobiological design [32]. But unlike other studies, we utilised a research design that incorporated two preferred music conditions (original tempo and time-stretched by 15%). This approach ensured any tempo-related effects were isolated. To the best of our knowledge, the current study is the first to investigate the effectiveness of acute music intervention and manipulation on morning peak isometric strength. The absence of significant improvements in MVC peak torque with and without stimulation, together with the lack of significant changes in perceived effort, exertion and arousal, may reflect an important feature of music-based ergogenic effects: the task may need to provide sufficient time for music to influence performance [5–7]. In the present study, both the brief MVC (3 s with the peak torque occurring in the first 1–2.5 s)

and the low-volume compound, multi-joint tasks may have provided limited time for music to exert a meaningful effect on strength or power output. Although the primary strength outcomes were not statistically significant, several condition effects were accompanied by medium to large effect sizes ($\eta^2_p = 0.06\text{--}0.20$), suggesting that any influence of music was inconsistent rather than clearly absent under these standardised morning conditions.

Even though no significant main effect of condition was observed for the principal bench press and back squat strength and power outcomes, the protocol was clearly sensitive to performance-related changes. Across both exercises, a robust main effect of load was evident, with average power, average velocity, peak velocity, displacement, mean propulsive velocity and rate of development of velocity generally highest at 40% of 1RM and lowest at 80% of 1RM, whereas time-related variables and perceptual responses increased as load increased. These findings are consistent with the fundamental force–velocity properties of skeletal muscle and have been demonstrated by us and others previously during submaximal loads using MuscleLab linear encoders and force platforms during complex movements [3,63]. This supports the internal validity of the testing protocol and suggests that the largely non-significant music findings are more likely to reflect a limited effect of music under these conditions rather than an insensitive test battery.

Although most cognitive condition outcomes were not significant, the Stroop-derived CW-error score was numerically higher in MUS than MUS15 ($p = 0.086$). Significant condition $\times$ time interactions were observed for WC-total and W-interference, with MUS showing the smallest pre–post change on both. This pattern suggests that music did not produce a broad enhancement of morning cognition but may instead have selectively influenced executive processes involved in inhibitory control and interference resolution. Although significant condition-by-time interactions were observed for two Stroop indices, these findings should be considered exploratory given the small sample size, the number of cognitive outcomes examined and the absence of consistent effects across the wider cognitive test battery. They do not establish an overall cognitive benefit of preferred music and require confirmation in adequately powered studies. Moreover, the present data raise the possibility that tempo manipulation, rather than enhancing performance, may have altered cognitive processing in a way that was not uniformly beneficial. However, given that most cognitive variables remained unchanged, these findings should be interpreted as selective and exploratory rather than conclusive. Exercise-induced effects should also be considered, as moderate to maximal resistance training has been demonstrated to induce central fatigue (short-term); once clear, norepinephrine and biomechanical drivers are elevated and hippocampal plasticity is improved [64,65]. Similarly, changes in catecholamine activity may contribute to alterations in arousal and attentional focus [64,66].

The expected psychological and perceptual mechanisms were only weakly affected by the intervention. During the MVC and lifting sections, felt arousal, feeling scale, attentional focus and PACES were not significantly different across conditions. This may weaken the argument that music improved strength and power through a strong affective, motivational or arousal-based pathway in the present study. This suggests that preferred music, even when time-stretched, may not have produced a sufficiently strong psychophysical response to enhance torque or velocity output under these conditions. This interpretation also contrasts with parts of the wider literature, where music has more consistently improved motivation, attentional focus, enjoyment, vigour or energy during repeated-effort resistance exercise [62,67,68], suggesting that the psychological pathway underpinning music's ergogenic effects may itself be task- and context-dependent.

One of the proposed mechanisms by which music may improve physical performance is through psychophysical pathways such as heightened arousal, increased motivation, improved attentional focus and greater readiness to exert maximal intent. In repetitive or

externally paceable tasks, music may also act as an external pacer promoting auditory–motor synchronisation and reducing perceived exertion. However, these mechanisms were not strongly supported in the present study. Subjective arousal, feeling scale, attentional focus and PACES were not significantly different across conditions during the MVC and lifting sections, despite small trend effects for perceived effort and exertion. This suggests that preferred music, even when accelerated by 15%, may not have produced a sufficiently strong psychophysical response to enhance torque or velocity output under these conditions, although participants’ perception of time was significantly modulated during the MVC. Whilst listening to music on its original tempo, participants perceived time on average as 2:13 min faster; when this same music was time-stretched by 15% the opposite was found, 1:24 min slower. The present findings indicate that any effect of music may have been more perceptual than neuromuscular, which is consistent with the sensitivity observed in temporal cognition. And this is in line with music working as a distractor, as it showed an effect during a task where participants are strapped into the chair whilst no effect was found during bench press and back squat where participants had more freedom to move during their rest periods.

That distinction becomes even more important when the methodological heterogeneity of the literature is considered. As summarised in Supplementary Table S1 [5,8–11,16,62,67–75], direct comparison across studies is difficult because participant characteristics, task selection, music prescription and environmental reporting vary considerably. Habitual sleep timing, exercise-time preference and chronotype are often poorly described, despite their likely relevance to morning performance, whilst task selection ranges from handgrip and MVC to repetitions-to-failure, squat jumps, and velocity-loss protocols. Music interventions are similarly inconsistent, with notable differences in track selection, preference matching, tempo, loudness, delivery method and timing of exposure. By contrast, the present study employed a more standardised morning design, including controlled sleep timing, exclusion of extreme chronotypes, a fixed early-morning testing window, overnight fasting, three familiarisation sessions, participant headphone delivery and loudness normalisation at ~75 dB and detailed environmental monitoring. As such, the present selective findings remain valuable, not because they show that music has no effect, but because they were obtained under conditions designed to reduce noise and reveal whether an effect was genuinely present.

Preferred high-intensity music has often been associated with improved strength task performance [5,8–11,16,62,67–75], although such effects appear to be highly task- and context-dependent [5,16]. In the present study, however, preferred music accelerated by 15% did not improve strength or power performance compared with control or the same music presented at its original tempo. This suggests that simply increasing tempo does not automatically enhance the ergogenic potential of music in maximal or low-volume resistance tasks. Rather, the present findings indicate that tempo manipulation may influence perceptual responses more readily than physical output [5]. Music may act as a distractor in a monotonous prolonged task. Notably, temporal cognition during the MVC task appeared sensitive to condition, with participants showing different estimations of elapsed time between music conditions. This effect was not present during the bench press and back squat where participant was free to roam around the testing area between each trial. This raises the possibility that accelerating preferred music may alter how demanding or time-consuming a session feels, even when objective performance is unchanged [76]. Accordingly, preferred music in its original form may be the more appropriate option when exploring the ergogenic effects of music in strength-based settings.

The largely non-significant effects on strength found in the present study should not be interpreted as evidence that music is ineffective per se, but rather that its ergogenic influence

may be narrower and more task-dependent than parts of the existing literature suggest. Many studies reporting positive effects with music interventions have used repetitions-to-failure protocols, repeated explosive efforts, squat jumps, or motivation-focused designs. In such studies, music has a greater opportunity to influence pacing, arousal and willingness to sustain effort. For example, Refs. [8–11,69,70] generally reported benefits in bench press repetitions to failure, velocity, power or motivation during repeated efforts, while other work has shown benefits in jump-based or affect-related outcomes [9,68]. In contrast, the present protocol was deliberately brief and tightly controlled, involving isolated MVCs and three repetitions at each load, 40, 60, and 80% of 1RM, in the bench press and back squat; these distinct loads enable us to experiment across different intensities of common training stress and understand effects on the force–velocity curve. Under such conditions, the window for music to exert cumulative motivational, pacing or synchronism-related effects may simply have been too small. This distinction is important, because it suggests that the present findings do not so much contradict the wider literature as help to define the boundaries within which music is most likely to act as an ergogenic aid.

5. Conclusions

Preferred music, whether played at its original tempo or accelerated by 15%, did not significantly improve morning isometric MVC with or without stimulation, % muscle activation, or the principal bench press and back squat strength and power variables in recreationally active males. These findings do not support our first hypothesis and suggest that, under a standardised morning protocol incorporating several key considerations from the chronobiology literature, music did not provide a robust acute ergogenic benefit for brief maximal or low-volume resistance tasks. We found that most cognitive outcomes were unchanged, although selective effects were observed in Stroop CW errors and temporal cognition during MVC, where participants perceived time as faster whilst on MUS than MUS15, indicating that music-related effects may have been more evident in executive or perceptual processing than in muscular output. Perceived affect and arousal, alongside attentional focus, was not affected by the presence of music; these are deemed to be the main mechanisms by which music may enhance performance. Taken together, the present findings suggest that the ergogenic influence of music may be narrower and more task-dependent than parts of the existing literature imply. Simply increasing the tempo of preferred music does not necessarily enhance its performance value in morning strength settings and may impact participants' task-dependent perception of time.

Perspective

In practice, preferred music may still be worthwhile as part of an athlete's pre-training routine, particularly for familiarity, enjoyment and selected perceptual or cognitive responses. However, the present findings do not support a clear acute ergogenic effect of preferred music on morning MVC or on low-volume submaximal bench press and back squat performance in trained young men. Importantly, increasing the tempo of preferred music by 15% did not improve strength or power outcomes compared with either control or the original tempo condition and therefore cannot currently be recommended as a strategy to enhance performance in this type of resistance protocol. Coaches and athletes should therefore be cautious in assuming that preferred or faster music will automatically improve morning lifting performance, especially during brief maximal or low-repetition tasks. Instead, music may be better viewed as an individually useful aid to session experience rather than a reliable ergogenic intervention. In this specific context, music could be used as a distraction, reducing the time-consumption feeling that one may have during an exercise session.

6. Limitations

Only young male participants volunteered for the present study, despite recruitment being open to both sexes. Therefore, more female-specific work and between-sex comparisons are needed, as biological sex may moderate the effects of music on strength, cognition and perceptual responses. Participants were recruited from undergraduate and postgraduate student populations, resulting in a relatively narrow age range (22.9 ± 3.7 years) and all were recreationally active, resistance-trained, intermediate chronotypes with no preference for time-of-day training. As such, the present findings may not be transferable to females, extreme chronotypes, elite athletes or other populations with different training histories or behavioural profiles. In addition, the current protocol compared preferred music at its original tempo with the same music time-stretched by 15%. For MVC peak torque, the a priori sample-size calculation indicated that 16 participants were required to achieve 80% statistical power at an alpha level of 0.05. However, following participant dropout, 14 participants completed all experimental sessions. The MVC analysis may therefore have been underpowered, and its nonsignificant findings should be interpreted cautiously. Furthermore, the original calculation used diurnal effect sizes and one-tailed t-tests rather than music-specific effects and the three-condition repeated-measures ANOVA, limiting its applicability to the present condition comparisons. The significant effect of load on displacement in both bench press and back squat also suggests that lifting form changed as the bar became heavier, despite familiarisation, and this may have influenced other linear encoder-derived variables. Personality traits, including introversion–extraversion, were not assessed. Consequently, we could not examine whether individual differences in personality influenced responses to preferred music or its increased tempo. Such differences may have contributed to variability in responses, although their contribution to the present findings remains uncertain. Furthermore, the sample-size calculation was based on neuromuscular outcomes rather than personality-related differences. The final sample of 14 participants would therefore provide limited scope for personality subgroup analyses, with a risk of failing to detect potentially meaningful differences.

7. Future Research

Future research should determine more precisely the conditions under which music can influence morning strength and cognitive performance. Direct comparisons between a wider range of tempo manipulations, different loudness conditions and delivery methods and exploration of why music may affect temporal cognition and how participants' time-perception may alter depending on task would help to clarify whether preference, tempo or intensity is the more important driver of any ergogenic or cognitive effect. This may be especially important in tasks that provide a greater window for pacing and cumulative motivational effects to develop, such as repetitions to failure, velocity-loss protocols, jump tasks, or sport-specific repeated efforts [9,10,67,68,75]. Future studies should also incorporate validated measures of personality, particularly introversion–extraversion, to investigate whether these traits moderate the effects of preferred music and tempo manipulation on neuromuscular, cognitive and perceptual outcomes. Sample sizes should be justified specifically for these moderation analyses. Analysing personality scores as continuous variables and presenting individual responses across conditions could help to characterise variation in responses without relying solely on group averages. As participants wore their own headphones, this might have affected the spectral characteristics, potentially affecting the acoustic stimulus across participants. Although within-participant means of delivery was standardised, future investigation should consider providing headphones and familiarising participants with these to reduce novelty prior to experimental sessions. Although participants completed three familiarisation sessions, study-specific reliability indices for the

performance outcomes could not be calculated because the session-level familiarisation data were unavailable for re-analysis. Consequently, small changes in test completion time, recall performance or error counts should be interpreted cautiously, particularly where their magnitude may fall within the normal test–retest variability reported for these instruments. Future work should also include females, novice or highly trained lifters and participants with different chronotypes or exercise-time preferences to improve the generalisability of the findings. Lastly, the inclusion of mechanistic measures related to arousal, attention, neural drive or cortical activity, such as electroencephalography (EEG) or functional near-infrared spectroscopy (fNIRS), may help to clarify whether music primarily influences perceptual, executive, or neuromuscular processes in the morning.

Supplementary Materials: The following supporting information can be downloaded at: <https://www.mdpi.com/article/10.3390/biomechanics6040097/s1>, Supplementary Methods S1: Cognitive battery of tests; Supplementary Methods S2: Isometric maximal voluntary contraction; Supplementary Methods S3: Bench press and back squat; Supplementary Methods S4: Perceptual and psychological outcomes; Supplementary Methods S5: Experimental Protocol and Measurements [5,32,44,47–58,77–88]; Supplementary Table S1: Comparison of current study and other authors to the Check list for consideration for diurnal variation studies.

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