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RESEARCH PAPER

Background music varying in tempo and emotional valence differentially affects cognitive task performance: experimental within-participant comparison

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Abstract The degree of stimulation provided by background music appears to affect performance on cognitive tasks. Moreover, individual differences influence what degree of stimulation is beneficial or detrimental. In a within-subject design, 40 participants (Mean Age: 26.15, SD: 2.99) completed cognitive tasks (immediate and delayed recall, phonemic fluency, trail-making) under varying (2 tempi: fast/slow × 2 valences: positive/negative) musical background conditions. Further, they completed questionnaires on individual differences (extraversion, noise sensitivity, annoyance/distraction by background noise). Performance was assessed using analyses of variance and mixed-effect models. Sensitivity analyses adjusted for stimulus liking and further individual characteristics. Fast (vs. slow) tempo was associated with better immediate recall (p = .002, η^2 = .08) and phonemic fluency (p < .001, η^2 = .16). Positive (vs. negative) valence was also associated with better immediate recall (p < .001, η^2 = .10) and phonemic fluency (p < .001, η^2 = .10). The association of positive valence with phonemic fluency was attenuated in those with above average Annoyance/Distraction by Background Noise. The latter also had a slower performance in the trail making test under positive background music. The association of fast tempo with verbal fluency was stronger among those scoring high in Noise Sensitivity. Overall, our results suggest that, with regard to concurrent cognitive performance, fast tempo, positively valenced background music is preferable over slow, negatively valenced background music. A deeper understanding of inter-individual differences could allow further individualisation of background music for cognitive task performance.

Keywords Background music · Cognitive performance · Arousal · Cognitive load

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Introduction

The role of background music in cognitive task performance remains contentious. On the one hand, arguments based on the cognitive capacity model (Kahneman, 1973) suggest that background music constitutes a distraction as it grabs attention and diverts limited processing resources from the task at hand. As a result, the 'cognitive load', i.e. the demand on cognitive processing, exceeds capacity and results in reduced performance (Sweller, 2011; 'cognitive load hypothesis'). On the other hand, it has been suggested that background music has the potential to increase alertness ('arousal'), positively influencing attention on the task at hand and thus improving performance (de la Mora Velasco et al., 2021; Kiss & Linnell, 2021).

In 2011, Kämpfe and colleagues synthesised evidence on background music's influence on cognition, finding a slightly negative effect. In the discussion, the authors highlighted that, based on large heterogeneity, no firm conclusions could be drawn as there must be moderating factors, including task specifics and type of music used. The authors suggested that music may only benefit tasks that are easy and/or largely automatized (i.e. when cognitive load is low), while it diverts attention from more complex and/or less automatized tasks (Kämpfe et al., 2011). In line with this, a 2023 meta-analysis found that music is beneficial for learning unless the material to be learned is highly complex (de la Mora Velasco et al., 2023). Concerning the question of which type of music may be most advantageous to learning, authors reported evidence for 2 musical characteristics. First, compared to music with lyrics, instrumental music appears to be associated with a more positive effect on learning. This may be the result of the former containing more information, and thus inducing a higher cognitive load. Second, faster music appears to be more beneficial than slower music.

The cognition enhancing effect of fast tempo music, more specifically fast tempo music of positive valence, has been argued previously in the context of the 'arousal-mood hypothesis' (Husain et al., 2002; Thompson et al., 2001). This hypothesis posits that listening to such music creates a state of elevated mood and arousal that is advantageous to subsequent cognitive task performance. Since the hypothesis' original formulation, this notion has been expanded to background music: fast, positive music is thought to raise arousal to the ideal level for concurrent performance on a diverse range of tasks (Bottiroli et al., 2014; Kiss & Linnell, 2022; Ritter & Ferguson, 2017).

However, musical valence is rarely pre-validated in terms of valence before use; 97% of musical stimuli used in emotion research are not validated beforehand (Warrenburg, 2020). Therefore, it remains uncertain whether *positive* valence is indeed best suited to support cognitive performance. Using stimuli that had been pre-validated as either 'joyful', 'agitating' or 'touching' (Proverbio et al., 2015a), Pr overbio and colleagues found 'touching' music (also described as 'slow' and 'sad') to enhance facial memory, while 'joyful' music (described as 'fast') impaired it (Proverbio et al., 2015a, 2015b). Conversely, accuracy on difficult arithmetic tasks was enhanced by both 'joyful' and 'touching' music (Proverbio et al., 2018). Thus, slow, negatively valenced music may have cognition-enhancing effects at least comparable to those of fast, positively valenced music.

The type of background music associated with better cognitive performance may also crucially depend on individual differences. Converging evidence points to extraversion/introversion playing a role in how background music influences performance, with extraverts having an increased benefit or decreased detriment from music compared to introverts (e.g. Cassidy & MacDonald, 2007; Dobbs et al., 2011; Furnham & Allass, 1999; Proverbio et al., 2018). Extraverts, who proposedly have a lower base arousal than introverts (Eysenck, 1963), may infer greater benefit from music-induced arousal. In line with this, extravert-specific performance advantages are absent when music is presumably minimally stimulating, i.e. 'soft' and 'slow' (Lehmann et al., 2019). Further support for the extravert/introvert distinction is provided by studies showing that noise sensitivity and distractibility by noise are overall lower in extraverts (Campbell, 1992; Seo et al., 2012). Yet, to our knowledge, an interaction between musical background conditions varying in tempo and valence and individual differences in extraversion or noise sensitivity/distractibility has not been investigated.

Thus, we aimed to investigate: (1) whether perceived emotional valence and tempo in background music differentially affect cognitive task performance, and (2) whether extraversion and/or noise sensitivity or distractibility moderated the effect of music on cognition. To this end, we presented participants with tasks to solve while background music varying in tempo and pre-validated perceived emotional valence (4 conditions, counterbalanced within-subject design) was playing. Based on the literature, we expected an interaction between tempo and valence. Specifically, we expected that positively valenced or slow, negatively valanced music would be found to be positively associated with performance. We also anticipated that extraversion and noise sensitivity/distractibility would moderate the effect of background music, so that those high in extraversion or with lower noise sensitivity/distractibility would benefit more from fast background music than those low in these characteristics.

Methods

Participants

Students were recruited via University newsletter advertisement. The inclusion criteria were: (1) age between 18 and 35, (2) not a professional musician, (3) no uncorrected visual or hearing impairments, (4) no self-reported cardiovascular disease, which could interfere with sensor measurements (see Procedure), and (5) no self-reported current/past diagnosis of depression. In an additional depression screening, we administered the Patient Health Questionnaire 9 (PHQ-9, Löwe et al., 2001). Based on the results, four individuals with scores indicating potential depression ($\geq$ 10, Kroenke et al., 2001) were excluded from the analysis.

Power analysis indicated that a sample size of n = 36 was needed to detect a within-participant effect of medium size (f = 0.25) in an analysis of variance, given an alpha level of 0.05 and a power of 0.95 (Faul et al., 2007). The final sample consisted of 40 participants (Mean Age: 26.15, SD: 2.99), the majority (57.5%) was male, and 92.5% were educated at College or University level (see Table 1). Session duration was 1.5–2 h. The experiment was administered in German (n = 6) or English (n = 34). Participants received course credit or a remuneration of 15 Euro. The experimental procedure was approved by the University Medicine Greifswald's Ethical Committee and the Ethical Committee of the Department of Social Science at the University of Kaiserslautern.

Material

Four musical stimuli were used. To ensure that pieces were comparable, criteria for selection were that they are (a) entirely instrumental (no human voices or environmental sounds), (b) performed by more than two instruments, and (c) part of a movie soundtrack (composed with the intent of transporting emotion; Warrenburg, 2020). Stimuli were chosen to vary along two dimensions: their tempo (fast vs. slow) and their emotional valence (positive vs. negative). The tempo (in beats per minute, bpm) was identified using Tempo-CNN in Python (Schreiber & Müller, 2018). The emotional valence perception was determined in a pre-validation study using a separate sample (Hofbauer & Rodriguez, 2023). We restricted our selection to the stimuli which, according to participants' perceptions, were least ambiguously expressing positive or negative valence (Hofbauer & Rodriguez, 2023).

Included stimuli were: (1) fast (130 bpm) with negative emotionality: *The Droid* by Jerry Goldsmith (Duration: 03:47), (2) slow (87 bpm) with negative emotionality: *The Revenant: Main Theme* by Ryuichi Sakamoto (Duration: 02:41), (3) fast (130 bpm) with positive emotionality: *The Return of the Eagle* by Atli Örvarsson (Duration: 02:58), and (4) slow (67 bpm) with positive emotionality: *First Youth* by Ennio Morricone (Duration: 2:15). Stimuli were presented at an intensity level averaging between 50 and 55 decibels.

Procedure

Testing took place in a brightly lit laboratory room. All participants received written and oral information about the study and gave written informed consent. In addition to cognitive and questionnaire data, sensor data were collected in this experiment (the corresponding data will be reported on in another paper). First, sensors (electrocardiogram, skin conductance electrodes, eye tracker) were attached and a 7 min baseline measurement taken. Four experimental conditions followed, differing only in the musical stimulus used (see Material). Each condition started with sensor measurements being taken at rest (5 min), continued with approximately 15 min of cognitive testing and concluded with questions on stimulus liking. Music was playing in the background during both rest and cognitive testing. The order of conditions was counterbalanced using a balanced Latin Square, resulting in four orders (1–2−3–4, 2–4−1–3, 4–3−2–1, and 3–1−4–2). Participants were pseudo-

Table 1 Demographic information

N =	40
Gender *n (%)*	
Men	23 (57.5%)
Women	17 (42.5%)
Education *n (%)*	
Secondary school (German Gymnasium)	2 (5%)
Vocational school	1 (2.5%)
College	5 (10%)
University	36 (82.5%)
Age *Mean (SD), Range*	26.15 (2.99), 20—34
SPHHQ *Mean (SD), Range*	
Annoyance/Distraction by Background Noise (SPHHQ-F1)	25.52 (5.16), 12—36
Importance of sound quality (SPHHQ-F2)	7.10 (2.05), 2 -10
Noise sensitivity (SPHHQ-F3)	9.85 (3.37), 3—15
Avoidance of unpredictable sounds (SPHHQ-F4)	9.45 (2.59), 3—14
Openness towards loud/new sounds (SPHHQ-F5)	10.78 (2.06), 6—15
Preferences for warm sounds (SPHHQ-F6)	7.40 (1.45), 4—10
Details of environmental sounds/music (SPHHQ-F7)	7.38 (1.75), 3—10
TIPI *Mean (SD), Range*	
Openness to experience (TIPI-O)	10.90 (1.93), 6—13
Conscientiousness (TIPI-C)	10.32 (2.72), 3—14
Extraversion (TIPI-E)	8.93 (2.70), 2—14
Agreeableness (TIPI-A)	9.75 (2.24), 6—14
Emotional Stability (TIPI-STAB)	9.28 (2.78), 2—13
PHQ-9 *Mean (SD), Range*	4.70 (1.96), 0—9

N sample size, *n* count, *PHQ-9* patient health questionnaire 9, *SP-HHQ* sound preference and hearing habits questionnaire, *SD* standard deviation, *TIPI* ten item personality index

randomly assigned an order of conditions, in an alternating fashion based on the order of their study participation. Upon conclusion of the experiment, participants were asked to answer questionnaires.

Stimulus Liking

After each condition, participants rated the following statements on a rating scale from 1 (“Does not apply at all”) to 7 (“Applies fully”): (1) “I perceived the music I just heard to be pleasant.” and (2) “I would listen to similar music in my free time.” These summed to give an overall stimulus liking score (range: 2–14).

Cognitive Testing

We selected three cognitive tasks for which previous research has suggested a positive effect of background music. *Word list recall* (1) is commonly used to give an indication of episodic memory function (e.g. Alenius et al., 2019). In a meta-analysis, episodic memory function has been shown to be most notably supported by background music (de la Mora Velasco et al., 2023). *Verbal fluency* (2) has also been observed to improve under some background music conditions (Bottiroli et al., 2014; Giannouli et al., 2019; Mammarella et al., 2007; Thompson et al., 2005). Finally, psychomotor speed, which we operationalise with the *trail-making test* (3) (Rammsayer & Stahl, 2007), has been found to be increased by background music (Bottiroli et al., 2014; Nittono et al., 2000). Each of the cognitive tasks were completed by each participant in every condition (see Fig. 1). Each of the cognitive tasks had four parallel versions that varied slightly in content to minimise practice effects. Participants were presented with a new version of each task in each condition. The parallel version used in each condition was fixed across participants. Details on scoring and differences between parallel versions are detailed in the sections below.

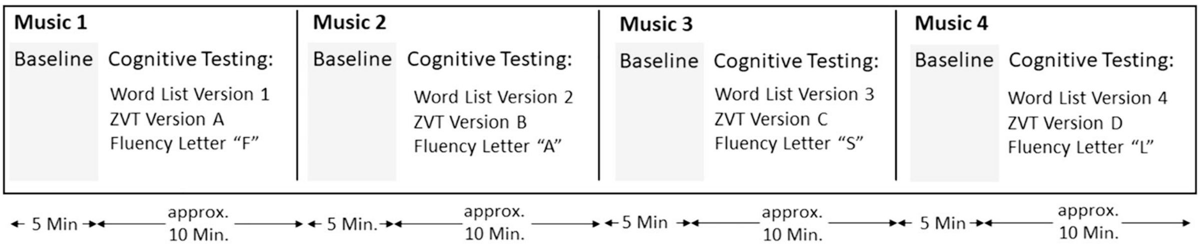

Fig. 1 Design of the Experimental Procedure. The figure depicts order 1–2–3–4 as an example. Alternative orders used were 2–4–1–3, 4–3–2–1, and 3–1–4–2. Numbers represent the following stimuli: (1) fast, negative emotionality, (2) slow, negative emotionality, (3) fast, positive emotionality, and (4) slow, positive emotionality

Immediate Word List Recall

In the word list recall task, participants are presented with 10 words, shown and read out one-by-one. Participants are then asked to repeat as many words as they are able to recall. This process is repeated three times in total, with the same list of words presented in a new order each time. The *immediate recall score* is the combined count of correctly recalled words (range: 0–30). Word lists used varied between parallel versions.

Phonemic Fluency

The phonemic fluency task is a test of verbal information retrieval and executive function (Dekhtyar et al., 2022). Participants are asked to produce as many words as they can that start with a specific letter. The letter is given by the instructor and varies between parallel versions (F, A, S, or L).

Trail-Making

We used the Zahlenverbindungstest (ZVT; Oswald & Roth, 1987) which is the German equivalent of non-alternating trail making. In this task, participants receive a sheet of paper containing the numbers from 1 to 90, which must be connected in serial order by drawing a continuous line between each number. They are instructed to be as fast as possible while maintaining accuracy. Errors have to be corrected. Time taken to complete the task is recorded. Parallel versions differ in the arrangement of numbers on the sheet.

Delayed Word List Recall

After a delay of approximately 5 min (i.e., the time which phonemic fluency task and trail making were completed in), participants are asked which of the ten words they had been presented with in the immediate recall task they still remembered. The *delayed recall score* represents the number of words recalled at this instance (range: 0–10).

Questionnaires

Demographic questionnaire

Participants reported their age, gender (Male, Female, Non-binary), and their highest level of schooling according to the German school system (Secondary School/Hauptschule, Secondary School/Realschule, Secondary School/Gymnasium, Vocational School/Berufschule, College/Fachhochschule, University/Universität).

Sound Preference and Hearing Habits Questionnaire (SP-HHQ)

The Sound Preference and Hearing Habits Questionnaire (SP-HHQ; Meis et al., 2018) uses 23 items. Items are rated on a scale from 1 ("Does not apply at all") to 5 ("Applies fully") and summed to give seven factor scores: Annoyance/Distraction by Background Noise (SPHHQ-F1, 8 items, range: 8–40), Importance of Sound Quality (SPHHQ-F2, 4 items, range: 4–20), Noise Sensitivity (SPHHQ-F3, 3 items, range: 3–15), Avoidance of Unpredictable Sounds (SPHHQ-F4, 3 items, range: 3–15), Openness towards Loud/New Sounds (SPHHQ-F5, 3 items, range: 3–15), Preferences for Warm Sounds (SPHHQ-F6, 2 items, range

2–10), and Details of Environmental Sounds/Music (SPHHQ-F7, 2 items, range 2–10).

Ten Item Personality Index (TIPI)

We used the Ten Item Personality Index (TIPI; Muck et al., 2007). It assesses the "Big 5" personality domains: Openness to Experience (TIPI-O), Conscientiousness (TIPI-C), Extraversion (TIPI-E), Agreeableness (TIPI-A), and Emotional Stability (TIPI-STAB). Two items describe each of the domains, one of these being reverse coded. The response scale ranges from 1 ("Disagree strongly") to 7 ("Agree strongly"), and items of a subscale are summed (subscale range: 2–14).

Analysis

Data analysis was conducted using R (Version 4.2.2) in RStudio (Version 2022.07.2, RStudio Team, 2020) and a significance level of $\alpha < 0.05$.

To evaluate the effect of tempo and perceived valence on performance, we first completed two-way ANOVAs of performance for each task (R packages: 'nlme4', 'lmerTest', and 'stats'). Residual plots were inspected for violation of the assumptions of normality and homoscedasticity. When the tempo-by-valence interaction was not significant, it was removed to avoid model misspecification. Second, to determine robustness of results, demographic confounders (Age, Gender, Education) and language (German vs. English) were included in ANCOVAs. Third, to investigate the role of individual differences of interest, we employed mixed-effect models with by-participant slopes (R packages: 'nlme4' and 'lmerTest'). In addition to valence, tempo, demographic confounders, and language, these included Extraversion (TIPI-E), Annoyance/Distraction by Background Noise (SPHHQ-F1), and Noise Sensitivity (SPHHQ-F3). Finally, we added terms for the interactions between individual differences of interest and tempo and valence one-by-one. Only significant interactions were retained.

If an interaction was observed, we used model coefficients to estimate the performance of (1) a person at an average level of the relevant characteristic and (2) a person with a high score (1 SD above the mean). For this purpose, gender was set to 'Male', education to 'University', and language to 'English'. Continuous predictors were kept at reference. Prior to the analyses, continuous predictors were mean-centred. As a result, the reference level is the mean, which is more meaningful than a reference of zero. If potential outliers (> 3 SDs deviation from mean) were detected for any cognitive task, analyses were repeated excluding these. If results diverged, the respective observation was excluded from the task-specific analysis as an influential outlier.

Sensitivity Analyses

Stimulus Liking

Final models constructed in the main analysis were repeated while controlling for stimulus liking, as previous research has shown that preference for a musical stimulus influences its perception and neural processing (Brattico et al., 2016). Liking ratings were mean-centred.

Further Individual Differences

We were also interested to see whether we would observe other individual differences in task performance. We thus expanded the final models constructed for each outcome in the main analysis to additionally include all other individual personality dimensions recorded (i.e., TIPI-O, TIPI-C, TIPI-STAB) and the remaining factors in sound preferences/hearing habits (SPHHQ-F2, SPHHQ-F4, SPHHQ-F5, SPHHQ-F6, SPHHQ-F7). Including interaction terms was not feasible as this induced problematic multicollinearity, as indicated by variance inflaction factors (R package 'performance').

Results

Cognitive Task Performance

Descriptives for task performance by Musical Background Stimulus and task are shown in Table 2.

Table 2 Average cognitive task performance by musical background condition

Background Stimulus	Mean (SD), Range			
	Immediate Word List Recall (n = 40)	Delayed Word List Recall (n = 40)	Phonemic Fluency (n = 40)	Trail making (n = 40)
Slow, positive	20.18 (3.27), 14–26	6.50 (1.85), 3–10	10.85 (5.43), 3–28	77.58 (15.87), 45–156
Slow, negative	19.05 (3.93), 11–27	6.03 (1.97), 3–10	9.80 (5.27), 2–26	74.85 (15.87), 48–111
Fast, positive	21.10 (3.57), 15–28	6.65 (2.23), 0–10	14.23 (6.01), 3–30	78.50 (22.94), 52–158
Fast, negative	20.18 (3.27), 14–26	6.30 (1.85), 2–10	11.50 (4.30), 4–21	76.70 (20.88), 44–140

SD standard deviation

World List Recall (Immediate)

Tempo, F (1, 118) = 10.14, $p = 0.002$, $\eta^2 = 0.08$, as well as a main effect of valence, F (1, 118) = 13.60, $p < 0.001$, $\eta^2 = 0.10$. There was no interaction between these (see Fig. 2). These effects were robust to adjustment for demographics (Table S1). Mixed-effect model output showed no effects of individual differences of interest and no interactions (Table 3).

Points/triangles indicate the unadjusted marginal means. Error bars represent the 95% confidence intervals surrounding the marginal mean estimates.

Delayed Word List Recall

No statistically significant effect of tempo, F (1,118) = 0.79, $p = 0.375$, $\eta^2 = 0.01$, or valence, F (3, 117) = 2.98, $p = 0.087$, $\eta^2 = 0.02$, was present in the two-way ANOVA of delayed word list recall performance and there was no interaction This was replicated adjusting for demographics (Table S2). Mixed-effect model output showed no statistically significant effects of individual differences of interest and no interactions (Table 3).

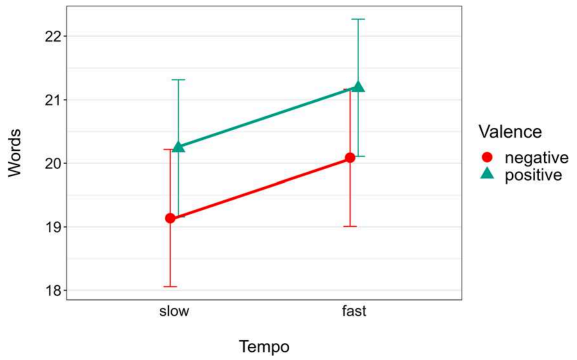

Fig. 2 Immediate Word List Recall Performance under Varying Musical Tempo and Valence

Phonemic Fluency

There was a main effect of tempo, F (1,118) = 23.17, $p < 0.001$, $\eta^2 = 0.16$, and a main effect of valence, F (1, 115) = 12.82, $p < 0.001$, $\eta^2 = 0.10$. There was no interaction between these (see Fig. 3). These effects were robust to adjustment for demographics (Table S3). In mixed-effect analysis, there was a significant association between Extraversion (TIPI-E) and task performance, β = 0.65, $p = 0.035$. Finally, there were statistically significant interactions between Annoyance/Distraction by Background Noise (SPHHQ-F1) and valence and between Noise Sensitivity (SPHHQ-F3) and tempo (see Table 3). The former indicates that the association of perceived positive valence with performance was weaker in those scoring higher on the SPHHQ-F1, β = −0.23, $p = 0.021$. The latter shows that the positive association of fast tempo with performance was more pronounced given higher SPHHQ-F3 scores, β = 0.39, $p = 0.012$. To illustrate, estimated performance with high SPHHQ-F1 (1 SD above the mean) was 11 words when listening to slow *positive* music (vs. 12 words for someone with average SPHHQ-F1), and 10 words when listening to slow *negative* music

Table 3 Results for mixed-effect models predicting cognitive task performance

Fixed Effects	Regression coefficients (St. Errors)			
	Immediate word list recall	Delayed word list recall	Phonemic fluency	Trail making
Intercept	18.87 (5.11)***	4.90 (2.34)*	20.35 (7.76)**	45.24 (28.40)
Tempo[1)]	0.95 (0.30)**	0.21 (0.24)	2.54 (0.51)***	1.39 (1.97)
Valence[2)]	1.10 (0.30)***	0.41 (0.24)	1.89 (0.51)***	2.26 (1.97)
TIPI-E[3)]	0.09 (0.20)	−0.04 (0.09)	0.65 (0.30)*	−0.02 (1.08)
SPHHQ-F1[3)]	0.01 (0.11)	0.00 (0.05)	0.08 (0.18)	−0.01 (0.66)
SPHHQ-F3[3)]	0.09 (0.17)	0.04 (0.08)	−0.02 (0.27)	1.03 (0.95)
Fast Tempo x SPHHQ-F3	n.a	n.a	0.39 (0.15)*	n.a
Positive Valence x SPHHQ-F1	n.a	n.a	−0.23 (0.10)*	1.06 (0.39)**

Results adjusted for age, gender, education, and language.

n.s non-significant interaction term not included in final model, *TIPI-E* Extraversion, *SPHHQ-F1* Annoyance/Distraction by Background Noise, *SPHHQ-F3* Noise Sensitivity, *St. Errors* Standard Errors

[1)] Reference tempo is slow; [2)] Reference valence is negative; [3)] Variable was mean-centred

*** *p < 0.001*, ** *p < 0.01*, * *p < 0.05*

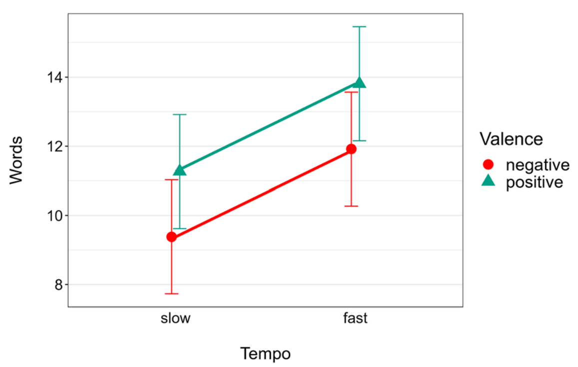

Fig. 3 Phonemic Fluency Performance under Varying Musical Tempo and Valence

(vs. 10 words). For fast music, the estimated performances would be 14 (vs. 14) for *positive* and 13 (vs. 13) for *negative* valence. For someone with high SPHHQ-F3, estimated performance was 13 words when listening to *fast* negative music (vs. 12 words for someone with average SPHHQ-F3), and 9 words when listening to *slow* negative music (vs. 9 words). For positive music, the estimated performances would be 15 words (vs. 14) for *fast* and 11 (vs. 11) for *slow* tempo. Removing 2 extreme observations did not affect results.

Points/triangles indicate the unadjusted marginal means. Error bars represent the 95% confidence intervals surrounding the marginal mean estimates.

Trail-Making

There were no significant effects of tempo, $F(3,118) = 0.47$, $p = 0.494$, $\eta^2 = 0.00$, or valence, $F(1, 118) = 1.25$, $p = 0.823$, $\eta^2 = 0.01$ on performance in the trail-making task. This was replicated after adjusting for demographics (Table S4). Mixed-effect modelling indicated a statistically significant interaction between Annoyance/Distraction by Background Noise (SPHHQ-F1) and valence, $\beta = 1.06$, $p = 0.007$, indicating that the association of perceived valence with performance was more pronounced given higher SPHHQ-F1 scorers. To illustrate, estimated performance for someone with high (1 SD above the mean) SPHHQ-F1 would be 87 s when listening to *positive* slow music (vs. 83 s for someone with average SPHHQ-F1), and 79 s when listening to *negative* slow music (vs. 79 s). For fast music, the estimated performances would be 89 s (vs. 84) for *positive* and 81 (vs. 81) for *negative* valence.

Sensitivity Analyses

Stimulus liking

Average liking ratings were 10.73 (SD: 2.83) for *slow, positive*, 9.97 (SD: 3.46) for *fast, positive*, 7.97 (SD: 3.11) for *slow, negative,* and 3.80 (SD: 2.17) for *fast,* *negative* music. In the fluency task, participants produced 0.36 words more for every liking-unit increase beyond the mean, β = 0.36, $p < 0.001$. Otherwise, controlling for liking did not affect results (not shown).

Further individual differences

For immediate word list recall, higher Conscientiousness (TIPI-C) was associated with improved performance, β = 0.63, $p = 0.018$, as was increased Annoyance/Distraction by Background Noise (SPHHQ-F1) β = 0.30, $p = 0.036$. Conversely, increased Avoidance of Unpredictable Sounds (SPHHQ-F4) was associated with impaired immediate recall, β = −0.88, $p = 0.002$. For the fluency task, Above average agreeableness (TIPI-A) was associated with improved performance, β = 1.11, $p = 0.012$. The association between Extraversion (TIPI-E) and fluency performance, which was significant in the main analysis, was no longer significant, β = 0.44, $p = 0.195$. Conversely, scoring higher in Importance of Sound Quality (SPHHQ-F2) was associated with impaired fluency, β = −1.12, $p = 0.041$. No individual differences were significantly associated with performance in the delayed recall or the trail-making task. Otherwise, results of main analyses were replicated (see Table S5).

Discussion

The main aim of this study was to determine whether background music of varying valence and tempo can modulate cognitive task performance. Our results indicate that fast tempo and perceived positive valence are associated with significantly better immediate recall and verbal fluency than slow tempo and negative valence. These findings were robust to sensitivity analyses.

The positive associations between music with fast tempo and perceived positive valence with performance on immediate recall and phonemic fluency are in line with the arousal and mood based explanations (Husain et al., 2002; Proverbio et al., 2018). More specifically, the significant associations for the immediate recall task support previous reports of fast background music having the capacity to positively affect the retention of simple information (de la Mora Velasco et al., 2023). Further, significant findings on the phonemic fluency task echo a previous report of a fluency advantage from listening to ‘fast’, ‘upbeat’ background music (Bottiroli et al., 2014). While the associations of tempo and valence with delayed recall performance did not reach significance, the data suggest that fast tempo and positive valence might be associated with more words recalled on this task. An arousal/mood based explanation is not the only explanation that can be reconciled with these results. Given that slow, negative music is more likely to induce negative thoughts and even rumination (Garrido, 2009; Koelsch et al., 2022), it would also appear plausible that cognitive activity induced by this type of music could be particularly distracting. Future research could explore this by systematically manipulating task difficulty.

Participant characteristics interacted differentially with the effects of tempo and perceived valence. First, the positive association between fast music and fluency performance was particularly pronounced for those who had a higher noise sensitivity. It is possible that individuals sensitive to noise might be more susceptible to entrainment, i.e. the adaptation of motor neuron firing rates to an external auditory rhythm, which might have allowed for increased verbal production (Thaut, 2015; Vuilleumier & Trost, 2015). Second, for the trail making test, the association between fast musical tempo and slower performance was particularly pronounced in those with higher annoyance/distraction by background noise. For those high in annoyance/distraction, fast tempo did not increase motor speed on this task, as would have been in line with an entrainment-based explanation. Instead, it appears to have been particularly disruptive, presumably because it heightened mood/arousal in a distracting fashion. Finally, the strength of the association between positive valence and fluency decreased with increasing annoyance/distraction by background noise. Speculatively, a person prone to negative reactions to background music might benefit less from any mood/arousal enhancement associated with positive valence. Advancing knowledge on such complex reactions to background music could allow individuals to match background music to task requirements and individual characteristics.

For the present investigation, we focus on the effect of *perceived* as opposed to experienced valence. In spite of the substantial correlation (Song et al., 2016), the latter may not fully align with the former. In the present sample, high liking ratings were observed not only for the positive stimuli but also for the slow, negatively valenced stimulus. Paradoxical enjoyment of slow, negative (‘sad’) music is a well-established phenomenon (Eerola et al., 2018). It is possible that this enjoyment may have affected the results; mood and/or arousal could have been heightened by the slow, negative stimulus. However, slow (vs. fast) tempo and negative (vs. positive) valence were not associated with significantly better performance on any of the tasks under investigation and controlling for liking did not affect results in the present study. Therefore, we have some confidence that there is a true effect of perceived valence.

Some advantages of this study are the use of pre-validated musical stimuli and a within-participant comparison of performance under background musical conditions varying in tempo and valence. However, the study is not without limitations. First, we can only make comparisons between different types of music; we cannot claim that any of these were more advantageous than no music. As such, our exploratory results need to be followed up by confirmatory experiments including a baseline condition. Since we used tasks for which performance has previously been observed to be superior under background music vs. silence, we expect that our results would be reproduced. Second, we selected the stimuli that were the least ambiguous in a pre-validation study (Hofbauer ans Rodriguez, 2023). As a result, we only used one stimulus per tempo x valence quadrant, which means that we cannot be certain that the observed effects will generalise to other stimuli. Musical stimuli are multidimensional, so aspects other than those intended may have influenced results (e.g. instruments in the orchestra). Replication using other pre-validated stimuli will be necessary to increase confidence in generalisability. Third, the slow stimuli differed in tempo: 87 bpm for negative valence and 67 for positive valence. This could have affected results, even though we observe no interaction between tempo and valence and would argue that our interpretation is thus not affected. Finally, we did not record whether participants normally worked or studied with background music. Habitual adaptation to background sound may have influenced performance (Crawford & Strapp, 1994; Kou et al., 2017). However, we believe that by assessing how annoying/distracting participants found background noise, we likely have a good proxy of habitual adaptation, as it appears unlikely that someone highly annoyed or distracted would normally use background music.

Conclusion

Taken together our results suggest that *fast* tempo and *positive* valence of background music, compared to slow tempo and negative valence, were associated with significantly better performance on the immediate recall and phonemic fluency task. The same trend, while non-significant, was observed for delayed recall but not for trail making. As individuals with high and average annoyance/distraction or in noise sensitivity appear to be differentially affected by background music, a deeper understanding of such inter-individual differences could allow individualisation of background music for concurrent cognitive task performance.

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Author contributions LMH, FSR and TL conceived and designed this study. LMH acquired data and carried out the statistical analysis, which was checked by FSR and TL. All authors interpreted the data. LMH produced the initial draft of the manuscript which was further revised by LMH, FSR and TL. All authors approved of final submission.

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Declarations

Conflict of interest The authors do not have a known conflict of interest to disclose.

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