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EFFECTS OF MUSIC TEMPO ON DRIVING PERFORMANCE AND ROAD SAFETY: A REPEATED-MEASURES DRIVING SIMULATOR EXPERIMENT

Ioannis Sidiropoulos[a], Dimitrios Nalmpantis[a,b,*], Evangelos Genitsaris[c]

[a]School of Civil Engineering, Faculty of Engineering, Aristotle University of Thessaloniki, PO Box 452, 541 24 Thessaloniki, Greece, jsidiropoulos3@gmail.com, dnalba@civil.auth.gr, https://orcid.org/0009-0005-5416-1541, https://orcid.org/0000-0002-6672-4082

[b]School of Applied Arts and Sustainable Design, Hellenic Open University, Parodos Aristotelous 18, 263 35 Patras, Greece, dnalba@civil.auth.gr, https://orcid.org/0000-0002-6672-4082

[c] Q-PLAN International Advisors PC, El. Venizelou 11, Thessaloniki, 55133, Greece; Evangelos Genitsaris: 0000-0002-3905-3981

Abstract: Music is frequently present during driving, yet its effect on driver performance remains inconclusive. This paper investigates whether driving without music, with medium-tempo music, and with high-tempo music produces differences in road-safety-related performance. We conducted a repeated-measures driving simulator experiment with 37 university students. Each participant completed the same urban driving scenarios under three conditions: i) no music, ii) medium-tempo music, and iii) high-tempo music. The scenarios included unexpected events and recorded reaction times, simulated crashes, traffic violations, vehicle-handling errors, speed-limit exceedances, and overall simulator scores. Repeated-measures analysis of variance (ANOVA) showed that music condition significantly affected reaction time ($F = 16{,}102$, $p < 0{,}001$, partial $\eta^2 = 0{,}091$), with lower reaction times under music conditions. Simulator score also differed significantly across conditions ($F = 3{,}341$, $p = 0{,}042$, partial $\eta^2 = 0{,}040$), with higher scores under high-tempo music than under no music. Although the overall effect on simulated crashes was significant ($p = 0{,}029$), Bonferroni-adjusted pairwise comparisons were not statistically significant. The findings suggest that music may improve selected aspects of simulator-based driving performance, while the specific role of tempo requires further investigation.

Keywords: music tempo; driving simulator; reaction time; driving performance; road safety.

1. INTRODUCTION

Listening to music is a routine part of modern mobility and, for many drivers, an almost automatic component of the in-vehicle environment. Previous research reviewed for this study indicates that most drivers listen to music while driving and that music is frequently used to regulate mood, reduce perceived stress, and make travel more pleasant (Brodsky & Slor, 2013; Dibben & Williamson, 2007; Hughes et al., 2013). From a road-safety perspective, however, music is not neutral. It may operate as an auditory or cognitive distraction, compete with environmental warning sounds, modify arousal, or alter the driver's emotional state. These

* Corresponding author. Tel.: +302310995811; e-mail address: dnalba@civil.auth.gr (D. Nalmpantis).

mechanisms can plausibly produce either beneficial or adverse changes in driving performance, depending on the characteristics of the music, the driver, and the driving task.

Empirical literature therefore provides mixed findings rather than a single directional effect, although a meta-analysis of 12 studies reported overall adverse associations between music, vehicle control, and collisions (Millet et al., 2019). Music can increase mental workload without necessarily degrading driving performance (Ünal et al., 2012), and some experiments have reported improved responses to visual or traffic-related stimuli when music is present (Be & Hirst, 1999; Navarro et al., 2018; Ünal et al., 2013). In contrast, studies of young and novice drivers have linked preferred or high-arousal music to riskier behavior, including higher speed, poorer visual scanning, or more driving errors (Babić et al., 2021, Brodsky & Slor, 2013). Other work has shown that the impact of music depends on factors such as volume, lyrics, emotional valence, familiarity, driver personality, age, and whether music is self-selected (Cassidy & MacDonald, 2009; Dibben & Williamson, 2007; Karageorghis et al., 2021; Niu et al., 2020; Slawinski & MacNeil, 2002). Consequently, statements that music is simply either safe or unsafe while driving are not sufficiently precise.

Tempo is one of the musical characteristics most consistently discussed as a potential moderator of driver behavior. Faster music can increase arousal and may encourage faster or more impulsive behavior, whereas lower-tempo music has been proposed to maintain calmness and reduce mental load (Li et al., 2019; Miao et al., 2021). At the same time, experimental evidence is not uniform. Navarro et al. (Navarro et al., 2018) reported conditions under which altering tempo did not translate into equivalent changes in driving behavior. Other experimental studies have also reported shorter reaction times under music in some task conditions (Be & Hirst, 1999; Ünal et al., 2013). These inconsistencies suggest examining tempo alongside ecologically relevant factors such as music preference, rather than as an isolated acoustic parameter.

A second issue concerns the study population. Previous research in Greece has identified relationships between willingness to pay for road-safety improvements and demographic, psychological, and behavioral factors (Beli & Nalmpantis, 2021). Young drivers have less driving experience and may be more susceptible to distraction, risk-taking, and the demands of simultaneous tasks (Brodsky & Slor, 2013); music-related distraction has also been shown to vary with driving experience and gender (Catalina et al., 2020). Evidence from Greek university students further indicates that social and peer-related factors can influence young drivers' road-safety behavior (Nalmpantis & Beli, 2025). The present paper therefore focused on a young university sample and required participants to hold a driving license and have at least one year of driving experience. We used a simulator because it allows repeated exposure to standardized hazardous events without placing participants or other road users at risk. The simulator environment also allowed us to collect multiple safety-related indicators, rather than relying on a single outcome such as speed or lane position.

The objective of this study was to examine whether driving performance differs across three within-subject conditions: i) no music, ii) self-selected medium-tempo music, and iii) self-selected high-tempo music. The study considered simulated crashes, clutch and engine-handling errors, turn-signal use, lane-keeping errors, excessive engine revolutions, speed-limit exceedances, overall simulator score, and reaction time to unexpected events. The primary research question was whether the presence and tempo of music were associated with systematic changes in these indicators. Given the contradictory previous evidence, the analysis was treated as exploratory rather than as a test of a single directional hypothesis.

2. METHODOLOGY

2.1. Participants

The sample included 37 students from Aristotle University of Thessaloniki (AUTh), Greece. Twenty-two (22) participants were male, and 15 were female. Age ranged from 19 to 27 years (M = 22,160, SD = 1,965), while driving experience ranged from one (1) to eight (8) years (M = 2,784, SD = 1,673).

All participants held a driving license and had at least one (1) year of driving experience. The study deliberately concentrated on relatively young drivers because the interaction between limited driving experience and music-related distraction or arousal is of road-safety interest. Table 1 summarizes participant characteristics (Note: M = mean; SD = standard deviation).

Table 1. Participant characteristics

Characteristic	Value
Participants	37
Male / female	22 / 15
Age, years	19–27; M = 22,160; SD = 1,965
Driving experience, years	1–8; M = 2,784; SD = 1,673

2.2. Driving simulator and scenarios

The experiment was conducted using the FOERST Passenger Car Simulator "Trainer" operated by the Transport Systems Research Group AUTh (FOERST Driving Simulators, 2020). Using simulation for controlled driver assessment also builds on earlier applications of interactive technologies for driver training and evaluation, which allow standardized driving situations to be examined without exposing participants to real-road risk (Nalmpantis et al., 2005). The simulator provides a conventional driver station with steering wheel, indicator and wiper controls, clutch, brake and accelerator pedals, and a gear lever. The visual environment is displayed on three 43-inch light-emitting diode (LED) screens arranged to provide an approximately 180-degree field of view. Vehicle and environmental sounds are reproduced through speakers located near the instrument cluster. We selected this speaker-based presentation instead of headphones to approximate the spatially diffuse auditory conditions of a real vehicle cabin (Brodsky, 2018).

The simulator's "Road Safety" module includes urban, rural-road, motorway, and mountain scenarios. We selected three (3) urban scenarios because together they covered a broad range of unexpected and safety-critical events. Examples included pedestrians or animals entering the roadway, parked vehicles moving unexpectedly into the driver's path, a parked-vehicle door opening, congested situations with restricted visibility, emergency vehicles requiring maneuvering, and a lead vehicle stopping suddenly. Each scenario lasted approximately 3–4 minutes, and the three-scenario sequence lasted about 14 minutes. At the end of each scenario, the simulator produced a performance score ranging from 0 to 100, reflecting completion time and recorded driving errors.

2.3. Music conditions

Three (3) experimental conditions were used. In the first condition, participants drove without music. In the second condition, they drove while listening to music at approximately 92 beats per minute (bpm), representing the medium-tempo condition. In the third condition, the target tempo was approximately 120 bpm, representing the high-tempo condition. Music intensity was maintained at approximately 65–70 decibels (dB), a moderate level selected to avoid both very low audibility and the stronger masking or distraction expected at high sound pressure levels.

To increase ecological validity, participants selected preferred tracks from a prepared list that met the target-tempo requirements. The list covered several genres commonly listened to by young adults, including metal, techno/electronic, rock, rhythm and blues (R&B), jazz, and pop.

Participants selected at least three (3) tracks, or more when required to cover the duration of the driving session. This design attempted to preserve the everyday feature of self-selected in-vehicle music while controlling tempo at the condition level. Table 2 summarizes the experimental conditions and their sequence.

Table 2. Experimental conditions and sequence

Stage	Condition	Music / task	Timing
Familiarization	Free driving	No experimental events; simulator familiarization	10 min
Condition 1	No music	Three urban road-safety scenarios	≈14 min
Condition 2	Medium tempo	Self-selected tracks, ≈92 bpm; same scenarios and order	≥1 week later
Condition 3	High tempo	Self-selected tracks, ≈120 bpm; same scenarios and order	≥1 week later

2.4. Procedure and performance measures

At the start of participation, we recorded demographic information and driving experience. Each participant then completed a 10-minute free-driving familiarization session. Participants then completed the three (3) urban experimental scenarios in a fixed sequence. The same participants returned for the medium- and high-tempo conditions, with at least one (1) week between sessions. The interval was intended to reduce explicit memory of the route and the timing of unexpected events. Nevertheless, the experimental conditions themselves were not counterbalanced: no music was always completed first, followed by medium tempo and then high tempo. This matters when interpreting changes that follow the same monotonic order.

The simulator automatically stored textual event messages and continuous performance outputs. Text messages were processed to obtain frequencies of specific errors, including “Accident”, “Wrong use of clutch”, “Engine stalled”, “Wrong use of indicator”, “Car off the roadway”, “Rpm too high”, and “Too fast”. Continuous outputs included the simulator score and reaction time between the onset of an unexpected event and the driver’s brake response. Table 3 summarizes the outcome definitions used in the analysis (Note: rpm = revolutions per minute).

Table 3. Driving-performance outcomes

Outcome	Operational definition in simulator data
Simulated crashes	Frequency of events recorded as Accident
Clutch error	Frequency of Wrong use of clutch messages
Engine stall	Frequency of Engine stalled messages
Turn-signal error	Frequency of Wrong use of indicator messages
Lane-keeping error	Frequency of Car off the roadway / lane-position errors
High engine speed (rpm)	Frequency of rpm too high messages
Speeding	Frequency of Too fast warnings
Simulator score	Scenario-level score generated by the simulator
Reaction time	Time from unexpected-event onset to braking response

2.5. Statistical analysis

We analyzed data in IBM SPSS Statistics 29 using repeated-measures analysis of variance (ANOVA), with condition as the within-subject factor. We used Mauchly's test to assess sphericity. When sphericity was violated, we used Greenhouse-Geisser-corrected results. Pairwise comparisons were adjusted using the Bonferroni procedure to control familywise errors. We evaluated statistical significance at $\alpha = 0,05$, and reported partial eta squared (partial η^2) as an effect-size measure where available.

The source data structure contained repeated records for some outcomes. Simulator scores were available at the scenario level and reaction times at the event level, producing more observations than participants for these two variables. The inferential statistics reported here reproduce the original analysis. This data structure should be considered when interpreting the size and precision of the score and reaction-time effects, because multiple observations from a participant are not independent.

3. RESULTS

3.1. Descriptive patterns across conditions

Descriptive results showed different patterns across the nine outcomes. Simulated crashes decreased from a mean of 0,800 in the no-music condition to 0,433 under medium-tempo music and 0,367 under high-tempo music. Engine stalls also decreased descriptively, from 3,300 to 1,867 and 1,600, respectively. Lane-keeping errors showed a smaller downward pattern. In contrast, speed-limit warnings were slightly more frequent in the music conditions than in the no-music condition. Clutch errors, turn-signal errors, and high-rpm events did not show a consistent monotonic pattern.

The clearest descriptive changes were observed for simulator score and reaction time. Mean simulator score increased from 23,220 without music to 34,171 with medium-tempo music and 38,585 with high-tempo music. Mean reaction time decreased from 1,538 s without music to 1,310 s under medium-tempo music and 1,249 s under high-tempo music. These patterns indicate improved simulator performance under the music conditions, although the inferential interpretation differs between score and reaction time and must be considered alongside the fixed

condition order. Descriptive means and repeated-measures ANOVA results for all outcomes are presented in Table 4.

Table 4. Descriptive means and repeated-measures ANOVA results

Outcome	No music	92 bpm	120 bpm	F	p	partial η^2
Simulated crashes	0,800	0,433	0,367	4,293	0,029	0,129
Clutch error	0,733	0,433	0,567	0,787	0,460	0,026
Engine stall	3,300	1,867	1,600	2,728	0,096	0,086
Turn-signal error	2,700	3,167	2,633	0,613	0,545	0,021
Lane-keeping error	1,767	1,633	1,367	0,750	0,477	0,025
High engine rpm	4,633	4,767	4,167	0,325	0,724	0,011
Speeding	8,567	9,467	9,167	0,384	0,644	0,013
Simulator score	23,220	34,171	38,585	3,341	0,042	0,040
Reaction time (s)	1,538	1,310	1,249	16,102	<0,001	0,091

For simulated crashes, the sphericity assumption was violated, and the Greenhouse-Geisser-corrected omnibus test was significant ($F = 4,293$, $p = 0,029$, partial $\eta^2 = 0,129$). However, no Bonferroni-adjusted pairwise comparison reached $p < 0,05$. The largest difference was between no music and high-tempo music (mean difference = 0,433 crashes, $p = 0,063$, 95% confidence interval (CI) [−0,017, 0,884]).

Thus, the data support an overall condition effect but not a statistically significant individual contrast after correction. The downward descriptive pattern should therefore be interpreted as suggestive rather than as evidence that high-tempo music reduces crashes.

3.2. Vehicle-handling and traffic-rule outcomes

No statistically significant condition effect was identified for clutch errors ($p = 0,460$), engine stalls (Greenhouse-Geisser $p = 0,096$), turn-signal errors ($p = 0,545$), lane-keeping errors ($p = 0,477$), high engine-rpm events ($p = 0,724$), or speed-limit exceedances (Greenhouse-Geisser $p = 0,644$). The absence of significant differences across these measures indicates that music and the two tested tempo levels did not produce broad, uniform changes in basic vehicle handling or rule-compliance indicators. This pattern matters because it prevents interpreting the results as a general improvement across all dimensions of driving performance.

Some outcomes nevertheless showed descriptively meaningful changes that did not reach statistical significance. Engine stalls were approximately halved in the music conditions relative to no music, but the corrected omnibus p-value was 0,096. Lane-keeping errors also decreased modestly across the three conditions. Conversely, speeding warnings were slightly higher under both music conditions. These mixed descriptive patterns reinforce the need to distinguish between specific performance dimensions rather than use a single global label of “better” or “worse” driving.

3.3. Simulator score and reaction time

Simulator score differed significantly across conditions after Greenhouse-Geisser correction, $F = 3,341$, $p = 0,042$, partial $\eta^2 = 0,040$. Bonferroni-adjusted comparisons showed that the no-

music condition had a significantly lower score than the high-tempo condition (mean difference = −15,366 points, p = 0,042, 95% CI [−30,347, −0,385]). The no-music versus medium-tempo comparison was not significant (p = 0,126), nor was the medium- versus high-tempo comparison (p = 1,000). The score results therefore support a difference between the two extreme conditions but not a stepwise dose-response effect of tempo.

Reaction time showed the strongest omnibus effect, F = 16,102, p < 0,001, partial η^2 = 0,091. Mean reaction time was lower in both music conditions than in the no-music condition. Bonferroni-adjusted pairwise comparisons were significant for no music versus medium tempo (mean difference = 0,228 s, p < 0,001, 95% CI [0,092, 0,363]) and for no music versus high tempo (mean difference = 0,289 s, p < 0,001, 95% CI [0,174, 0,404]). The difference between medium and high tempo was small and not statistically significant (mean difference = 0,061 s, p = 0,853). Thus, the reaction-time result is more consistent with a difference between silence and music than with a specific additional benefit of increasing tempo from 92 to 120 bpm.

Table 5 presents Bonferroni-adjusted pairwise comparisons for outcomes with significant omnibus effects (Note: CI = confidence interval).

Table 5. Bonferroni-adjusted pairwise comparisons for outcomes with significant omnibus effects

Outcome	Comparison	Mean difference	p	95% CI
Simulated crashes	No music − 92 bpm	0,367	0,162	−0,097 to 0,830
Simulated crashes	No music − 120 bpm	0,433	0,063	−0,017 to 0,884
Simulated crashes	92 bpm − 120 bpm	0,067	1,000	−0,204 to 0,337
Simulator score	No music − 92 bpm	−10,951	0,126	−23,904 to 2,002
Simulator score	No music − 120 bpm	−15,366	0,042	−30,347 to −0,385
Simulator score	92 bpm − 120 bpm	−4,415	1,000	−21,136 to 12,307
Reaction time	No music − 92 bpm	0,228	<0,001	0,092 to 0,363
Reaction time	No music − 120 bpm	0,289	<0,001	0,174 to 0,404
Reaction time	92 bpm − 120 bpm	0,061	0,853	−0,077 to 0,199

4. DISCUSSION

4.1. Main findings

The study examined a broad set of simulator-based safety outcomes under no music, medium-tempo self-selected music, and high-tempo self-selected music. Three findings stand out. First, most vehicle-handling and traffic-rule indicators were not significantly affected by condition. Second, reaction time was shorter under both music conditions, with no significant difference between medium- and high-tempo music. Third, simulator score was higher under high-tempo music than under no music, while simulated crashes showed a significant omnibus condition effect but no significant Bonferroni-adjusted pairwise contrast. Taken together, the results suggest that music was associated with changes in selected performance dimensions rather than a uniform transformation of driving behavior.

This distinction matters for road-safety interpretation. A lower reaction time to unexpected events is directly relevant to hazard avoidance, while the simulator score combines several elements of task performance. By contrast, the absence of significant changes in speeding, lane keeping, turn-signal use, or vehicle-handling errors indicates that music did not consistently alter every observable behavior. The results therefore do not justify a general statement that high-

tempo music makes driving safer. A more defensible interpretation is that, within this simulator protocol, music was associated with faster responses and higher overall scores, whereas evidence for a tempo-specific incremental effect was limited.

4.2. Relation to previous research

The reaction-time pattern is compatible with experimental work reporting that music can maintain arousal or improve responses to peripheral or unexpected stimuli (Be & Hirst, 1999; Navarro et al., 2018; Ünal et al., 2013). Ünal et al. (Ünal et al., 2012; Ünal et al., 2013) argued that music can increase mental effort or arousal without necessarily degrading driving performance, and the present results similarly show that music conditions did not produce broad deterioration in handling or compliance. Navarro et al. (Navarro et al., 2018) also emphasized that tempo effects are context-dependent and do not translate mechanically into proportional changes in driving behavior. The lack of a difference between 92 and 120 bpm reaction times in the present study is consistent with that caution.

Other studies point in the opposite direction. High-arousal genres and high-tempo music have been associated with higher speed, poorer visual scanning, riskier decision making, or stronger distraction among young drivers (Babić et al., 2021; Brodsky & Slor, 2013; Miao et al., 2021; Niu et al., 2020). Brodsky and Slor (Brodsky & Slor, 2013) particularly emphasized young novice drivers' vulnerability when preferred music captures attention. These findings matter because the current sample was also young and participants selected preferred tracks. The present experiment therefore does not resolve the wider debate; rather, it adds evidence that, under moderate volume and standardized urban simulator tasks, self-selected music need not cause measurable deterioration across a broad range of driving indicators.

Music preference may help explain part of this discrepancy. Cassidy and Macdonald (Cassidy & MacDonald, 2009) reported more positive performance and experience with self-selected music, whereas other studies have suggested that preferred music may increase engagement with the music itself and thereby distraction (Brodsky & Slor, 2013). The current protocol deliberately allowed self-selection within tempo-controlled lists. This improves ecological validity because drivers normally choose their own music, but it also means that tempo was not isolated from genre, familiarity, lyrics, or emotional associations. The experiment therefore tests realistic packages of self-selected music at two tempo levels rather than pure tempo manipulation.

Volume is another relevant moderator. The present music level of approximately 65–70 dB lies between the lower and higher intensities examined by Karageorghis et al. (Karageorghis et al., 2021). Very loud music may mask warning cues or increase cognitive load, while moderate music may support arousal without causing the same degree of interference. The absence of strong negative effects in the present study should consequently not be extrapolated to high-volume listening. Similarly, the study did not evaluate music as a fatigue countermeasure; previous long-distance simulator research found tempo-dependent effects on fatigue and attention, with medium-tempo music providing the most favorable balance among the tested tempo conditions (Li et al., 2019).

4.3. Interpretation of the apparent improvement

The descriptive ordering of several outcomes, particularly crashes, score, and reaction time, appears to favor the later music conditions. One plausible interpretation is that music reduces stress or raises arousal to a more effective level for urban tasks. Driver stress itself has also been conceptualized as an important safety-related mechanism, with elevated internal stress under

time pressure associated with aggressive driving and accident-prone traffic conditions (Nagkoulis et al., 2024). This is consistent with literature showing that music can influence mood and physiological activation during driving (Fairclough et al., 2014, Navarro et al., 2019, Ünal et al., 2013; van der Zwaag et al.; 2012, van der Zwaag et al., 2013). However, the present design also contains a major alternative explanation: condition order was fixed. Every participant completed no music first, medium tempo second, and high tempo third. Consequently, familiarization with the simulator, routes, and event structure could produce an improvement that follows the same order as tempo. The one-week interval reduces event memory but does not eliminate procedural learning.

This limitation is especially relevant for the score and reaction-time outcomes because these measures showed the greatest improvements. The significant improvement in reaction time from no music to both music conditions, while medium and high tempo did not differ, can be interpreted as either a beneficial effect of music relative to silence or a practice effect after the first session. The high-tempo score advantage over no music is similarly compatible with both explanations. A counterbalanced or randomized condition order is therefore necessary before a causal benefit of music, and particularly of high tempo, can be established.

The crash result also requires cautious interpretation. The omnibus repeated-measures test was significant, but the Bonferroni-adjusted no-music versus high-tempo contrast had $p = 0,063$ and its confidence interval included zero. It should not be described as statistically significant.

The mean reduction is potentially interesting for hypothesis generation, but stronger evidence would require a larger sample, more crash opportunities, and an analysis designed around participant-level event rates.

4.4. Methodological limitations and future research

Several limitations constrain generalization. The sample was relatively small and concentrated in a narrow young-adult age range. Results may differ among novice teenagers, middle-aged drivers, older drivers, or highly experienced professional drivers. The simulator provides controlled exposure to hazards but cannot reproduce all motivational, perceptual, and risk-related features of real-road driving. We fixed the moderate music volume; therefore, we did not evaluate interactions between tempo and volume. Moreover, participants selected preferred tracks from a list, so genre, lyrics, familiarity, and emotional content were not experimentally separated from tempo.

The repeated-observation structure of the score and reaction-time analyses is another limitation. Scenario-level scores and event-level reaction times generated more records than participants. A stronger future analysis would aggregate observations within participants or use a multilevel mixed-effects model that explicitly nests scenarios and events within drivers. This would preserve the available repeated information while correctly modeling dependence among observations from the same participant. For the event-frequency outcomes, count-based mixed models could likewise provide a more natural representation than normally distributed ANOVA when counts are sparse or skewed.

Future experiments should counterbalance the order of no-music, medium-tempo, and high-tempo conditions, maintain the same minimum washout interval, and recruit a larger, more heterogeneous sample. A factorial design could independently vary tempo, intensity, and self-selection. Physiological measures such as heart rate or respiration could help distinguish arousal and stress mechanisms from simple practice effects. Finally, a controlled on-road study using a dual-control vehicle could assess whether the simulator findings generalize to real traffic, provided that safety and ethical requirements are satisfied.

5. CONCLUSIONS

This repeated-measures driving simulator study found that music condition was associated with selected, but not universal, changes in driving performance. Reaction time to unexpected events was significantly lower under both medium- and high-tempo music than under no music. Overall simulator score also differed across conditions, with a significant advantage for high-tempo music relative to no music. Simulated crashes showed a significant overall condition effect, but individual Bonferroni-adjusted comparisons were not statistically significant. Clutch errors, engine stalls, turn-signal errors, lane-keeping errors, high engine-rpm events, and speed-limit exceedances did not differ significantly across conditions.

The evidence therefore supports a cautious conclusion: self-selected music at moderate volume may coexist with, and in some measures may be associated with, improved simulator performance. The data do not establish that higher tempo itself is safer, because the medium- and high-tempo reaction-time conditions did not differ and because participants completed the experimental conditions in a fixed order. Counterbalanced studies with larger samples and participant-level or multilevel statistical models are needed before making practical road-safety recommendations about music tempo.

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