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The effects of music and auditory stimulation on autonomic arousal, cognition and attention: A systematic review☆

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A R T I C L E I N F O

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A B S T R A C T

According to the arousal-mood hypothesis, changes in arousal and mood when exposed to auditory stimulation underlie the detrimental effects or improvements in cognitive performance. Findings supporting or against this hypothesis are, however, often based on subjective ratings of arousal rather than autonomic/physiological indices of arousal. To assess the arousal-mood hypothesis, we carried out a systematic review of the literature on 31 studies investigating cardiac, electrodermal, and pupillometry measures when exposed to different types of auditory stimulation (music, ambient noise, white noise, and binaural beats) in relation to cognitive performance. Our review suggests that the effects of music, noise, or binaural beats on cardiac, electrodermal, and pupillometry measures in relation to cognitive performance are either mixed or insufficient to draw conclusions. Importantly, the evidence for or against the arousal-mood hypothesis is at best indirect because autonomic arousal and cognitive performance are often considered separately. Future research is needed to directly evaluate the effects of auditory stimulation on autonomic arousal and cognitive performance holistically.

1. Introduction

Auditory stimulation, such as music and noises, has long been recognized for its profound effects on human emotions and behaviors. For example, auditory stimulation can induce changes in autonomic activity, the involuntary physiological responses that regulate various bodily functions (McConnell et al., 2014; Salimpoor et al., 2009; Schäfer and Sedlmeier, 2011). Moreover, certain types of auditory stimulation (e.g., some music genres or sounds at specific frequencies) have been proposed to affect cognitive functioning, i.e., improving or worsening cognitive performance during certain tasks or activities (Baum and Chaddha, 2021; Engelbregt et al., 2019; Schellenberg et al., 2007; Thompson et al., 2012). Furthermore, associations between autonomic activity regulation, emotions (e.g., the James-Lange theory of emotion; Lange and James, 1922), and cognition (Quadt et al., 2022) have been theorized, but the underlying mechanisms are not clear.

The potential positive impact of music on cognitive performance started to be researched several decades ago when music-related improvements in spatial task performance were first reported (Rauscher et al., 1993). This positive effect is sensationalized with the term "Mozart effect", as Rauscher and colleagues observed improvements in cognitive functioning following exposure to Mozart's music. However, others have argued that the positive effect of music on cognition is likely dependent on changes in arousal and mood after listening to the music (Thompson et al., 2001). This is named the arousal-mood hypothesis. The hypothesis predicts that music induces changes in arousal and mood, which in turn influence cognition. In support of the arousal-mood hypothesis, increased arousal and better spatial task performance were

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observed among participants who heard music in fast major mode (Husain et al., 2002). Importantly, arousal, mood, and enjoyment explained 58.2 % of the variance in spatial task performance. Therefore, certain types of auditory stimulation could lead to changes in arousal and mood, affecting cognitive performance. It can be speculated that this relationship could follow an inverted U-shape (Yerkes and Dodson, 1908), where optimal levels of arousal – achieved via appropriate auditory stimulation – would lead to improvements in performance, compared to low or excessive arousal.

Arousal is defined as the state of alertness and attentiveness and has been theorized that changes in physiological or autonomic measures reflect changes in the level of alertness and attentiveness. Autonomic arousal is regulated by the autonomic nervous system (ANS), which is considered to consist of three distinct systems: sympathetic, parasympathetic, and enteric systems (Gibbons, 2019). This paper focuses on the autonomic indices of arousal that are suggested to reflect activities in the sympathetic nervous system, which predominates during "fight-or-flight" situations, and the parasympathetic nervous system, which predominates during resting states. Consequently, an increase in arousal may stem from heightening of sympathetic activity, inhibition of parasympathetic activity, or a combination of both. It is, thus, crucial to emphasize that each index of autonomic arousal may not contribute to the regulation of arousal in the same way.

Many organs are innervated by both sympathetic and parasympathetic branches, and this entails that the majority of the autonomic indices of arousal reflect the dynamic relationship between the two branches (Mathôt, 2018; Shaffer and Ginsberg, 2017). Thus, metrics that reflect activity in either the sympathetic or parasympathetic branches are considered in this paper. Among the various metrics, this paper reviewed studies that investigated heart rate (HR), heart rate variability (HRV), and pupil reactivity in response to auditory stimulation. This paper additionally reviewed studies that measured electrodermal activity, an autonomic index of arousal that reflects purely sympathetic activity (Braithwaite et al., 2013). Changes in autonomic activity after listening to music have long been documented (Davis and Thaut, 1989; Harrer and Harrer, 1977; Rickard, 2004; Salimpoor et al., 2009; Schäfer and Sedlmeier, 2011). However, different types of music may have differential effects on autonomic indices. For example, music composed in minor mode and with a slow tempo, which is common in sad music, may have a limited impact on autonomic activity (Verrusio et al., 2015). Furthermore, individual differences in musical preference may mediate how arousing a piece of music is. For instance, the intensity of induced emotions by classical music is influenced (i.e., enhanced) by the preference for the music (Kreutz et al., 2008). Therefore, it seems likely that higher arousal would be induced if the music was preferred by the individual.

The arousal-mood hypothesis seems plausible because the brain network/region that is activated by music, especially preferred music regardless of genre or inclusion of lyrics (Wilkins et al., 2014), is also involved in regulating autonomic activity (Raichle, 2015; Zhang et al., 2014). However, there is mixed evidence for the arousal-mood hypothesis. Increased arousal without changes in cognitive performance (Hirokawa, 2004) and enhanced cognitive performance without changes in arousal (Smith et al., 2010) have been observed.

Besides music, other sounds can be systematically manipulated to produce various types of noise (i.e., colored noise) and beats. In this review, we will focus specifically on ambient noise, white noise, and binaural beats. White noise contains all frequencies on the power spectrum, and it uses a mix of these frequencies to create a static-like sound (e.g., TV static). While it is commonly conceived that ambient noises (e.g., noises from machines or traffic) negatively affect cognitive performance (Jafari et al., 2019; Jahncke et al., 2011), white noise may have a positive effect on cognitive performance (Angwin et al., 2018; Baum and Chaddha, 2021; Othman et al., 2020). A potential mechanism by which white noise may benefit cognitive performance is neuromodulation in dopaminergic regions and their connectivity with the superior temporal sulcus, a region that plays a role in attention modulation (Rausch et al., 2014). Slight improvements in recognition memory were observed when exposed to white noise in comparison to control sounds (e.g., a sinus tone). The improvements were positively correlated with the stronger connectivity between dopaminergic regions and the superior temporal sulcus. Critically, the effect of white noise on cognitive performance also seems to follow an inverted U-shape, as predicted by the arousal-mood hypothesis (Britton and Delay, 1989). However, there is a paucity of studies directly investigating autonomic activity concerning white noise and cognitive performance, despite the indirect evidence.

Binaural beats, on the other hand, are the auditory perception of a single tone that emerges when each ear is administered tones of similar frequencies separately (e.g., 200 and 210 Hz). Binaural beats are believed to stem from cognitive or neural entrainment (Vernon et al., 2014). Binaural beats are usually categorized based on frequency (i.e., alpha, beta, gamma, and theta). A meta-analysis reported overall positive effects of binaural beats on cognition (Garcia-Argibay et al., 2019). However, theta-frequency binaural beats might negatively impact cognition. The effects of binaural beats on cognitive performance are consistent with the arousal-mood hypothesis; improvements in mood are paralleled with more correct target detections in a vigilance task (Lane et al., 1998). Similar to the literature on music and white noise, there is a lack of studies examining the effects of binaural beats on autonomic activity in relation to cognition.

The purpose of this systematic review is to critically examine and synthesize the current literature on the impact of music and auditory stimulation (i.e., ambient noise, white noise, and binaural beats) on autonomic activity and its subsequent effects on cognitive performance. By elucidating the findings in this field, this review aims to contribute to a comprehensive understanding of the relationship between auditory stimulations, autonomic activity, and cognitive performance, offering valuable insights for future research and practical applications.

2. Materials and methods

We pre-registered the study on PROSPERO (CRD42022339659) and followed the most recent PRISMA guidelines (Page et al., 2021) for reporting the main findings of the systematic review. The PRISMA Checklist is included in Supplement 1. We systematically searched Pubmed, Web of Knowledge/Science, Ovid Medline, Embase and APA PsycInfo until 25th April 2022, with no language/type of document restrictions. The search strategy included terms associated with the following domains: a) Autonomic arousal, b) Music or auditory stimulation, and c) Attention, cognitive and executive functioning (more details can be found in Supplement 2). We selected cohort or cross-sectional studies reporting on changes in autonomic arousal associated with auditory stimulation, i.e., music, sounds or noise, in people of any age without any health, neurodevelopmental or psychological/psychiatric conditions.

Titles and abstracts of the retrieved references were screened independently by two authors (MC and JC) to identify potentially eligible studies; disagreements were resolved through discussion between authors and consultation with the project supervisor (AB). The full text of each article marked as eligible was assessed by four authors (MC, JC, HB, SH) for final inclusion and cross-checked by (ZJC). The information extracted from retained studies were: study design and characteristics, sample characteristics (size, age, % females, ethnic distribution), type of auditory stimulation implemented, cognitive mechanism(s) investigated and task utilized, measure of ANS functioning collected (cardiac, electrodermal, pupillometry, etc.), narrative description of main findings. We report a narrative synthesis of the main findings, considering the collected data made it unsuitable for a meta-analysis to be carried out. Specifically, as illustrated in Table 1, when analyzing the studies included in the review, we realized there was too much heterogeneity. In most cases, conducting a meta-analysis on a specific outcome measure

Table 1
Summary of main findings of the studies included in the review, split by type of auditory stimulation investigated, ANS domain and measure, and cognitive function investigated.

Auditory stimulation	ANS Domain	ANS Measure	Cognitive function	Study	Sound intensity	Total length of task/ experiment	Main findings
Ambient/ intermittent noise	Cardiac	Heart rate	Working memory	Abbasi, 2018	55, 65, 70, & 75 dBA	15 min (during)	Increased HR & lower accuracy
				Abbasi, 2020	55 & 75 dBA	15 min (during)	Increased HR & lower accuracy
				Keith, 2019	75 dBA	Unclear (during)	Increased HR & marginally lower performance
				Love, 2021	54.5 & 59.5 LAeq	Unclear (during)	Increased HR & no effect on performance
			Psychomotor	Bhattacharya, 1991	70 & 100 dBA	Unclear (during)	Increased HR & negative effect on performance
				Wheale, 1982	66 & 100 dBA	40 min (during)	No changes in HR & performance
			Vigilance/sustained attention	Boucsein, 1996	50 & 80 dBA	50 h (during)	No changes in HR & performance
				Carter, 1989	92 dBA	55 min (during)	Increased HR, lower accuracy & faster latency
			Visual-spatial reasoning	Damián-Chávez, 2021	78 LAeq	Unclear (during)	Increased HR & lower performance
			Arithmetic ability	*Medvedyk, 2019*	*Unclear*	*Unclear (during)*	*Increased HR & task performance not reported*
				Takahasi, 2001	70 dBA	60 min (during)	No changes in HR & task performance not reported
			Unclear	Mosskov, 1977	83.5–91 dBA	30 min (15 mins before and 15 mins during the task)	Decreased sinus arrhythmia & worse performance
		Heart rate variability	Working memory	Abbasi, 2018	55, 65, 70, & 75 dBA	15 min (during)	Increased HRV & lower accuracy
				Abbasi 2020	55 & 75 dBA	15 min (during)	Increased HRV & lower accuracy
				Love, 2021	54.5 & 59.5 LAeq	Unclear (during)	Decreased RSA & no effect on performance
			Vigilance/sustained attention	Boucsein, 1996	50 & 80 dBA	50 h (during)	No changes in HRV & performance
				Carter, 1989	92 dBA	55 min (during)	No changes in HRV, lower accuracy & faster latency
			Unclear	Kristiansen, 2009	65 LAeq	35 min (during)	No changes in HRV & performance
	Electrodermal	SCL/SCR	Working memory	Keith, 2019	75 dBA	Unclear (during)	Increased SCL & no effect on performance
				Love, 2021	54.5 & 59.5 LAeq	Unclear (during)	No changes in SCL & performance
			Vigilance/sustained attention	Boucsein, 1996	50 & 80 dBA	50 h (during)	Increased EDA & no changes in performance
	Pupil	Pupil size/ diameter	Arithmetic ability	*Medvedyk, 2019*	*Unclear*	*Unclear (during)*	*Variation in pupil size & task performance not reported*
White/colored noise	Cardiac	Heart rate	Attentional control/ inhibitory control	Basow, 1974	100 dBA	1–2 h (during)	No changes in HR & changes in performance dependent on anxiety level (low-improved, moderate-deteriorated, high-constant)
				Röttger, 2021	77–89 dBA	12 min (during)	Changes in HR and performance between noise and no-noise no reported
			Short-term memory	Conrad, 1973	93 dBA	20 min (during)	No changes in pulse rate & performance
			Unclear	Gibson, 1966	Unclear	Unclear (during)	Greater cardiac acceleration & no changes in completion times
				Hershman, 1979	85 dBA	Unclear (during)	HR decelerated & longer completion times
			Information processing	Finkelman, 1979	90 dBA	Unclear (during)	No changes in HR & more errors made
			Memory retrieval	Jennings, 1988	50 & 90 dBA	2.5 h (during)	No changes in HR & increased recall error
		Heart rate variability	Attentional control/ inhibitory control	Röttger, 2021	77–89 dBA	12 min (during)	No changes in HRV & performance between noise and no-noise not reported
	Electrodermal	SCL/SCR	Attentional control/ inhibitory control	Basow, 1974	100 dBA	1–2 h (during)	No changes in SCR & changes in performance dependent on anxiety level (low-improved, moderate-deteriorated, high-constant)
			Working memory	Han, 2021	Unclear	20 min (during)	No changes in EDA & improved performance
Music	Cardiac	Heart rate	Attention	Bishop, 2009	55 & 75 dBA	Unclear (before)	No changes in HR & faster RT in fast-loud condition
			Working memory and attentional control	Scholz, 2019	Max 55 dBA	Unclear (during)	Increased heartbeat frequency in the music condition compared to silence but no changes in cognitive performance

(*continued on next page*)

Table 1 (*continued*)

Auditory stimulation	ANS Domain	ANS Measure	Cognitive function	Study	Sound intensity	Total length of task/ experiment	Main findings
			Facial memory	Proverbio, 2015	89 dBA	Unclear (during)	Emotionally touching music increased HR & improved memory; rain/joyful music impaired memory
			Driving ability	van der Zwaag, 2012	Unclear	70 min (before)	No changes in IBI & lower driving speed in positive music vs no music
			IQ	Cockerton, 1997	Unclear	5 min (during)	No changes in HR & improved performance
			Semantic memory	Van Strien, 1997	40–91 dBA	Unclear (during)	No changes in HR & better left visual field performance in threatening music
		Heart rate variability	Attentional control/ inhibitory control	Kirk, 2021	Unclear	30/60 min (during)	Increased HRV & better performance
			Reading comprehension	Madjar, 2020	70 ± 5 % volume scale	20–25 min (during)	No changes in HRV & worse reading comprehension
			Working memory and attentional control	Scholz, 2019	Max 55 dBA	Unclear (during)	No changes in HRV and cognitive performance in the music condition compared to silence
	Electrodermal	SCL/SCR	Attentional control/ inhibitory control	Irish, 2006	40–50 dBA	45 min (during)	No changes in GSR, no effects on errors of commission & longer RT in music condition
Binaural beats	Pupil	Pupil size/ diameter	Vigilance/sustained attention	Robison, 2021	Beta-frequency (16 Hz)	20 min (during)	No changes in pupillary response & longer reaction times

Note. The study in *italics* did not specific the type of noise used. EDA: electrodermal activity; GSR: galvanic skin response; HR: heart rate; HRV: heart rate variability; IBI: interbeat-interval; RSA: respiratory sinus arrythmia; RT: reaction time; SCL: skin conductance level; SCR: skin conductance response.

and task/condition would have included less than two studies.

3. Results

3.1. Main description of studies

Out of 11,243 records initially retrieved from multiple sources, 5334 were duplicates. 5909 records were therefore screened, out of which 5686 were excluded after title/abstract screening. Among the 216 records assessed for eligibility at full-text screening, 185 were further excluded (PRISMA flowchart and reasons for exclusion are reported in Fig. 1), leaving 31 records that were included in the narrative synthesis.

Twenty-one studies investigated the effects of noise on autonomic activity in relation to cognitive performance or attention (see Table 1 for an overview of the findings of the studies included in the review). Specifically, 12 studies investigated the effects of ambient/intermittent noise on cardiac indices, either as the sole measure ($n = 9$) or in combination with electrodermal indices ($n = 3$). Five studies investigated the effects of white noise on cardiac indices as the sole measure, two in combination with electrodermal indices, and one solely on electrodermal indices. One study did not specify the type of noise used and investigated the effects of noise on heart rate and pupil size. The intensity of the noise stimulation ranged from 50 to 100 decibels (dBA; see Table 1). Nine studies investigated the effects of music on autonomic arousal in relation to cognitive performance or attention. Eight of these investigated cardiac indices and one electrodermal indices. Most of the studies (87.5 %) used music without lyrics and one compared music with lyrics to music without lyrics and silence. Only one study investigated the effects of binaural beats (200 Hz in one ear and 216 Hz in another).

3.2. Studies investigating the effects of noise on autonomic arousal

3.2.1. Heart rate (HR)

Nineteen studies measured the effects of noise on heart rate. Nine studies reported an increased heart rate following noise exposure, of which six reported a negative impact on cognitive performance (Abbasi et al., 2018, 2020; Bhattacharya et al., 1991; Carter and Beh, 1989; Damián-Chávez et al., 2021; Keith et al., 2019). These six studies used ambient noise or intermittent noise (a mix of ambient noise and silence). Two studies reported no impact (Gibson and Hall, 1966; Love et al., 2021). They used white noise and ambient noise, respectively. One study did not report any impact on cognitive performance (Medvedyk et al., 2019).

Seven studies reported no significant changes in heart rate following noise exposure. Nevertheless, two out of these seven studies – both implementing white noise – reported worse cognitive performance (Finkelman et al., 1979; Jennings et al., 1988). Three studies reported no significant changes in cognitive performance (Boucsein and Ottmann, 1996; Conrad, 1973; Wheale and O'Shea, 1982). Boucsein and Ottmann (1996) and Wheale and O'Shea (1982) used traffic noise, whereas Conrad (1973) used white noise. Two other studies did not report changes or the changes in cognitive performance were dependent on other factors (Basow, 1974; Takahashi et al., 2001).

Two studies reported a deceleration in heart rate and worse cognitive performance following exposure to white noise and traffic noise (Hershman and Gibson, 1979; Mosskov and Ettema, 1977) respectively. Changes in heart rate and cognitive performance were unclear when comparing noise and no-noise conditions in one study (Röttger et al., 2021).

3.2.2. Heart rate variability (HRV)

There are numerous metrics for HRV, and each may reflect predominantly sympathetic or parasympathetic activity, or a combination of both (Shaffer and Ginsberg, 2017). Seven studies measured HRV as a cardiac index for autonomic arousal. Two studies reported increased low frequency/high frequency (LF/HF) ratio, an indicator that reflects predominantly sympathetic activity (Pagani et al., 1997), and poorer cognitive performance following exposure to ambient noise (Abbasi et al., 2018, 2020). Four studies reported no significant changes in HRV. Two out of these four studies reported no significant changes in cognitive performance (Boucsein and Ottmann, 1996; Kristiansen et al., 2009), using traffic noise and office noise, respectively. The exact HRV metric used in Boucsein and Ottmann (1996) was unclear, but it appears to be similar to root mean square of successive RR interval differences (RMSSD), which reflects mainly parasympathetic activity (Laborde et al., 2017). Kristiansen et al. (2009) measured mean RR-interval length (reflects the dynamic between sympathetic and parasympathetic activity; Surawicz and Knilans, 2008). One study reported better cognitive performance without changes in RMSSD and RR-interval between quiet and intermittent noise groups (Carter and Beh, 1989). One did not report changes in RMSSD, respiratory sinus arrhythmia (RSA; an indicator of parasympathetic activity), and cognitive performance following noise

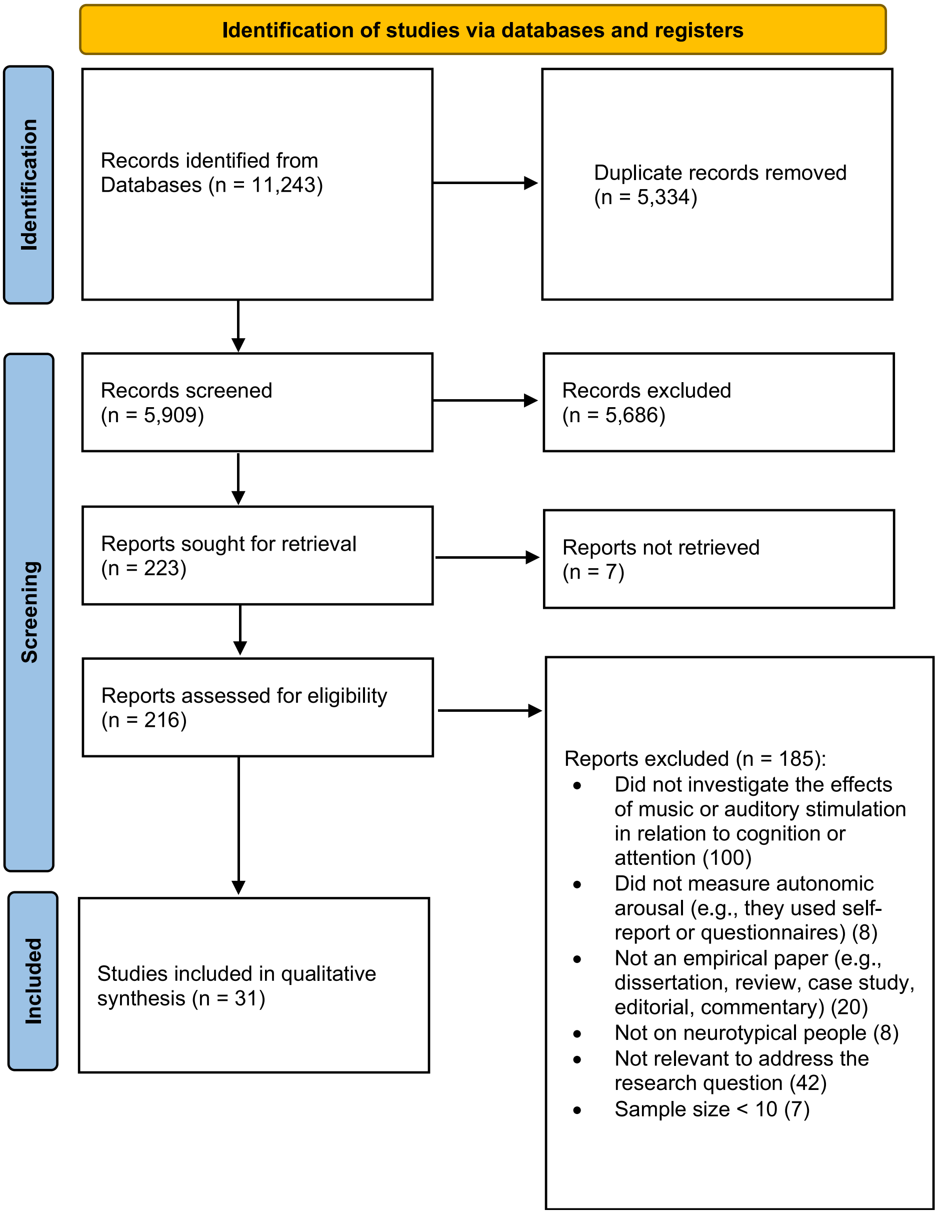

Fig. 1. PRISMA flowchart.

exposure (Röttger et al., 2021). One study reported decreased RSA and no significant changes in cognitive performance following exposure to workplace noise (Love et al., 2021).

Overall, ambient noise appears to be more consistent in manifesting effects on the cardiac indices of arousal (i.e., increased heart rate and LF/HF ratio, both reflecting the input of the sympathetic branch). This is often accompanied by poorer cognitive performance, though some studies also reported no changes in both cardiac indices of arousal and cognitive performance. The findings on whether white noise has an impact on cardiac indices of arousal and cognitive performance are mixed.

3.2.3. Electrodermal measures

Electrodermal activity can be quantified with two types of measures: the tonic, slow-acting skin conductance level (SCL) and the phasic, fast-changing skin conductance response (SCR). Three studies compared SCL between noise and silence conditions (Keith et al., 2019; Love et al., 2021; Röttger et al., 2021). Two out of these three studies (Keith et al., 2019; Röttger et al., 2021) reported increased SCL following exposure to noise, whereas one study reported no changes in SCL (Love et al., 2021). Keith et al. (2019) reported no changes in cognitive performance despite an increase in SCL following exposure to intermittent noise. Whereas Love et al. (2021) did not find any changes in SCL and cognitive performance. The other study did not compare cognitive performance between conditions (Röttger et al., 2021). One study reported no significant changes in SCL and cognitive performance following exposure to workplace noise (Love et al., 2021). Two studies did not specify whether they looked into the SCL or SCR, and instead compared EDA between conditions. Han et al. (2021) found no changes in EDA but an improvement in cognitive performance when exposed to white noise. In contrast, Boucsein and Ottmann (1996) found an increase in EDA but no changes in cognitive performance in the condition where participants were exposed to 80 dBA of traffic noise compared to 50 dBA of traffic noise. One study compared SCR between noise and no-noise conditions. The study reported no significant changes in SCR following exposure to white noise, and changes in cognitive performance were dependent on other factors (Basow, 1974).

Overall, there is no clear indication of whether ambient noise or white noise affects electrodermal indices of arousal and cognitive performance.

3.2.4. Pupil measures

Only one study investigated the effects of noise on pupil size in combination with a cardiac index in relation to cognitive performance and attention. The study reported variation in pupil size but did not indicate whether it increased or decreased significantly when noise was introduced (Medvedyk et al., 2019). Changes in cognitive performance were also not reported. The evidence regarding the pupil index of autonomic arousal in relation to noise is lacking to reach any kind of conclusion.

3.3. Studies investigating the effects of music on autonomic arousal

3.3.1. Heart rate (HR)

Six studies measured heart rate as a cardiac index for autonomic arousal. One study reported an increased heart rate in response to emotionally touching music and an improvement in facial memory (Proverbio et al., 2015). The same study also reported impaired memory performance in response to rain/joyful music, but it was unclear if it was accompanied by significant changes in heart rate. Another study reported an increased heart rate while listening to relaxing music without any changes in performance on multiple cognitive tasks (Scholz et al., 2019). Four studies reported no significant changes in heart rate following exposure to music. Three out of the four studies found an improvement in cognitive performance despite no changes in heart rate (Bishop et al., 2009; van der Zwaag et al., 2012; Van Strien and Boon, 1997), and one study found no significant impact on cognitive performance (Cockerton et al., 1997).

Overall, all but one study reported no effects of music on HR. Moreover, the characteristics of music varied widely across studies. Even when comparisons were limited to studies that manipulated a specific characteristic (e.g., valence), there were also no consistent patterns (e.g., Proverbio et al., 2015; van der Zwaag et al., 2012; Van Strien and Boon, 1997). Hence, it seems that music might not have a consistent effect on HR.

3.3.2. Heart rate variability (HRV)

Three studies measured HRV as a cardiac index of arousal. Kirk et al. (2022) found an increase in RMSSD and better cognitive performance following exposure to music. Whereas Madjar et al. (2020) found poorer reading comprehension performance despite no significant changes in HRV (exact metric unclear). As reported above, Scholz et al. (2019) found an increase in HR but no changes in any of the HRV measures (e.g., LF/HF, NN50, RMSSD) and performance in cognitive tasks while listening to relaxing music.

Only one study reported change in HRV using an indicator of parasympathetic branch. Therefore, it remains inconclusive given the small number of studies and mixed findings.

3.3.3. Electrodermal measures

One study investigated the effects of music on electrodermal indices in relation to cognitive performance or attention. Irish et al. (2006) found no significant changes in galvanic skin response (both SCL and SCR) and attention following exposure to music. However, a longer RT was observed in the music condition. The evidence regarding the electrodermal index of autonomic arousal in relation to music is lacking to reach a conclusion.

3.4. Studies investigating the effects of binaural beats on autonomic arousal

Only one study investigated the effects of binaural beats on autonomic index of arousal in relation to cognitive performance or attention. Robison et al. (2022) found no significant changes in pupillary response but poorer attention (longer RT) in response to music. The evidence on whether or how binaural beats affect autonomic arousal in relation to cognitive performance is lacking to reach a conclusion.

4. Discussion and conclusion

We provided an overview of the literature examining the effects of auditory stimulation on different indices of autonomic and physiological arousal. Specifically, we identified 31 studies investigating the effects of noise, music, or binaural beats on autonomic activity and cognitive performance. Most of which investigated cardiac measures. The overall findings from these studies are either heterogeneous or limited to reach a clear conclusion. Given that most studies focused on cardiac measures, we will try to dissect and devote most of our discussion to cardiac measures.

Noise, especially ambient noise, appears to affect cardiac measures (i.e., increasing heart rate) quite consistently, accompanied by poorer cognitive performance. However, this is not the case with music; some studies found no changes in cardiac measures but did find improvements/impairments in cognitive performance. On the contrary, other studies found changes in cardiac measures but *no* alterations in cognitive performance in response to music. Hence, there seems to be a consistent relationship between noise, arousal, and cognitive performance, but the relationship with music is contradicting.

Noise and music differ in their acoustic properties. Noise tends to be static (e.g., white noise) or irregular (e.g., ambient/intermittent noise). Music, on the other hand, is rhythmic with predictable patterns (in most cases). In extreme cases, noises that are considered environmental pollutants have been suggested to have detrimental effects on the brain at the micro (e.g., molecular) and macro (e.g., morphological) levels (Arjunan and Rajan, 2020). This could further cascade into increased risks of certain diseases (e.g., cardiovascular; Münzel et al., 2021). In line with this, our findings suggest that short-term exposure to ambient noise (usually environmental pollutants) tends to increase autonomic arousal and negatively impacts cognitive performance. We further speculate that consistent or intermittent exposure to ambient noise might lead to ANS dysregulation, which has been implicated as a common pathway to a variety of conditions and diseases (Salvioli et al., 2015; Thayer et al., 2010; Yeater et al., 2022). White noise and music are not commonly regarded as environmental pollutants. This might explain why findings on white noise and music in relation to autonomic arousal and cognitive performance are mixed in comparison to findings on ambient noise.

Functionally, music, white noise, and ambient noise also differ widely. Ambient noise is not designed or manipulated to serve any meaningful purpose. Conversely, white noise is devised to mask ambient noise and aid sleeping. Music has even wide-ranging functions such as personal (e.g., emotion regulation and memories), social (e.g., social bonding), and practical purposes (e.g., music as a background and diversion; Boer and Fischer, 2012). These variations may contribute to more consistent evidence for the relationship between ambient noise, arousal, and cognitive performance than for white noise and music. Notwithstanding the differences in functions, all auditory stimulations could be regarded as distractions, especially when the auditory stimulations is unwanted. Regardless of the arousal levels, it is expected that if one finds auditory stimulation distracting, their performance will be poorer. This might explain why preference can be a possible moderator of the effects of auditory stimulation on autonomic activity and cognitive performance (e.g., Nantais and Schellenberg, 1999).

Apart from differences in acoustic and functional properties, individual differences in the optimal level of arousal might also explain the mixed findings. Eysenck's theory of personality underlies that at rest, extroverts are likely to be under-aroused and introverts are likely to be optimally aroused. This implies that if an introvert is further stimulated by auditory stimulation, it will lead to a drop in performance, because the arousal would become suboptimal. In contrast, an extravert at rest who is auditorily stimulated would likely show an *improvement* in performance because the arousal level would be elevated to a (more) optimal level. Findings appear to be in favor of Eysenck's theory of personality, according to a mini-review (Küssner, 2017). However, support for Eysenck's theory of personality mostly came from observations that auditory stimulation has a detrimental effect on introverts' performance instead of having a positive effect on extroverts' performance. This implies that without determining the baseline level of arousal, as in the case of most studies, findings are likely to be complicated by individual differences in the optimal level of arousal. Future studies should aim to determine the baseline arousal when testing whether the effects of noise or music on autonomic arousal and cognitive performance follow an inverted U-shape.

Task characteristics, such as length and difficulty, might also determine whether auditory stimulations have an influence on autonomic arousal and task performance (Szalma and Hancock, 2011). It seems unlikely that auditory stimulations would further improve or worsen task performance if the task is extremely easy (ceiling effect) or difficult (floor effect). Moreover, auditory stimulations can interact with difficulty levels such that they improve performance on relatively easy tasks but impair performance on relatively difficult tasks (Keith et al., 2019). To further complicate matters, task difficulty can also have a direct impact or have an interaction with auditory stimulations on autonomic activity. Abbasi et al. (2018) found that HRV differed from baseline across different workload (difficulty) conditions. Keith et al. (2019) demonstrated an increased HR among adolescents for an easier task (forward span), but no changes in HR for a more difficult task (backward span) with the addition of noise. This implies that comparing results across studies with different task difficulties could be nearly impossible and could have contributed to why our review found mixed results.

We considered changes in sympathetic and parasympathetic activities to reflect changes in arousal in the current review and reviewed papers that shared the same view. However, what autonomic indices reflect differs between publications, which adds to the already complex puzzle. Autonomic activities, especially sympathetically driven cardiac reactivity (e.g., pre-ejection period; PEP), have been posited to reflect task engagement or effort mobilization (Wright, 1996). Drawing on the motivation intensity theory (Brehm and Self, 1989), and the psychophysiological research of Obrist et al. (1978), this approach has received substantial empirical support (e.g., see Richter et al., 2016, for a review). Additionally, a recent study found that when exposed to noise, participants who were assigned stimulus color for cognitive tasks showed stronger PEP, reflecting greater effort, in comparison to participants who were able to personally choose stimulus color (Falk et al., 2023). This again echoes our discussion on the potential influence of preference on the relationship between auditory stimulation and task performance. Specifically, preference or freedom to choose the type of stimulus/stimulation that one receives may moderate one's physiological response and performance in a task. Moreover, there is ample evidence for the effects of musically induced mood on effort assessed as cardiac reactivity during task performance (e.g., Gendolla and Krüsken, 2001, 2002). It is therefore important to acknowledge that changes in autonomic activity might reflect other abstract psychological constructs rather than arousal per se. This opens avenues for future studies to tease apart the contribution of autonomic activity to effort and arousal, which differ conceptually.

Relatedly, this leads to our next point on whether the relationship between autonomic activity and arousal is well established. One of the approaches to testing whether such a relationship is warranted is to demonstrate that autonomic activity is related to subjective arousal (i.e., construct validation approach; Richter and Slade, 2017). Covariation of autonomic activity with self-reported (subjective) arousal has been reported (e.g., Gomez and Danuser, 2004; Sato et al., 2020). However, this covariation does not seem to be consistent; SCL increased with arousal ratings for music but not for noises, whereas HR increased with arousal ratings for noises but not for music (Gomez and Danuser, 2004). This inconsistency is also reflected in the results of our review. If objective and subjective arousal are merely different ways to measure the same construct, they probably should always be related to each other. However, findings show that autonomic activity and subjective arousal might not always be related. This again suggests that autonomic activity might not reflect arousal per se. Despite the complexity and potential extraneous influences, we believe the role arousal plays in the relationship between auditory stimulation and task performance deserves further study. A logical first step would perhaps involve determining whether autonomic activity and self-reported measures reflect the "same" arousal, which necessitates a clear definition of arousal.

Our review revealed a dearth of studies investigating electrodermal or pupillary measures in response to noise and music in relation to cognitive performance. From the meager literature that we reviewed, many of the findings suggest no effect of noise or music on electrodermal measures. Similarly, we found only one study that examined the effects of binaural beats on pupillary measures in relation to cognitive performance. Thus, we are unable to draw any conclusions with respect to these domains. Moreover, the imbalance in our review highlights some interesting issues, such as the lack of investigation of autonomic activity in studies using music/binaural beats to induce various levels of arousal. Nevertheless, there is some evidence that noise, music, and binaural beats could potentially influence electrodermal or pupillary measures and cognitive performance independently (Baum and Chaddha, 2021; Bruschi et al., 2023; Engelbregt et al., 2019; Gingras et al., 2015; McConnell et al., 2014).

The findings of our review should be viewed in light of some limitations. Despite not having any language and age restriction, all but one paper reviewed were in English and sampled mostly young adults. Our registered inclusion/exclusion criteria might have been (too) restrictive, as we included only studies that either explicitly or implicitly treated autonomic activity as a proxy for arousal. Studies that assessed autonomic activity within the context of auditory stimulations and task performance (regardless of the studied psychological constructs such as effort, motivation) could have provided additional insights to our research question. Importantly, most of the included studies did not directly examine whether autonomic activity mediates the effects of auditory stimulation on cognitive performance. Rather, autonomic activity and cognitive performance were often considered separately. Thus, our findings inherently can only provide indirect evidence for or against the arousal-mood hypothesis.

To conclude, findings on ambient noise tend to indirectly support the arousal-mood hypothesis; there is perhaps a significant increase in autonomic arousal beyond the optimal level and a decline in cognitive performance in response to ambient noise. However, the arousal-mood hypothesis is yet to be subjected to direct examination. Furthermore, there is insufficient evidence to reach a conclusion with respect to music, white noise, and binaural beats and their effects on autonomic activity and cognitive performance. Hence, more studies are warranted to meticulously tease apart the effects of each auditory stimulation on autonomic activity and cognitive functioning while keeping relevant factors in mind.

CRediT authorship contribution statement

Zhong Jian Chee: Writing – review & editing, Writing – original draft, Visualization, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Chern Yi Marybeth Chang:** Writing – review & editing, Data curation. **Jean Yi Cheong:** Writing – review & editing, Data curation. **Fatin Hannah Binte Abdul Malek:** Writing – review & editing, Data curation. **Shahad Hussain:** Writing – review & editing, Data curation. **Marieke de Vries:** Writing – review & editing, Writing – original draft, Supervision, Conceptualization. **Alessio Bellato:** Writing – review & editing, Writing – original draft, Supervision, Software, Resources, Project administration, Methodology, Investigation, Conceptualization.

Data availability

Data are presented in the manuscript.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ijpsycho.2024.112328.

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