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Do emotions evoked by music modulate visuospatial working memory capacity? A physiological study

Fabiana Silva Ribeiro[1,2], Flávia H. Santos[3] and Pedro B. Albuquerque[1]

Abstract

Previous studies have shown that emotions evoked through music can have transient effects on cognitive performance. Considering the importance of working memory (WM) in the processing of new information, in this study, we investigated the impact of positive and negative emotions evoked through music on visuospatial WM performance using a within-subjects design. Moreover, we concomitantly recorded the participants' physiological responses during listening to musical stimuli. Seventy-eight participants were allocated to counterbalanced positive, negative, and neutral emotional inductions through music (EIM) followed by an adaptive visuospatial WM task. Results revealed that participants' visuospatial WM performance was increased after positive EIM compared with negative and neutral EIMs transiently. We also observed increased skin conductance levels during positive EIM compared with baseline and a lower heart rate throughout positive EIM than the other conditions. Overall, these findings suggest that music evoking positive emotions can boost visuospatial WM performance. This is the first study to explore cognitive performance after EIM and physiological responses to musical stimuli simultaneously, which may have important practical implications since we engage in cognitively demanding activities after listening to music that could evoke happy or sad emotions.

Keywords

music, emotions, working memory, emotional states, visuospatial capacity

[1]Human Cognition Lab, School of Psychology, University of Minho, Braga, Portugal
[2]Department of Social Sciences, University of Luxembourg, Esch-sur-Alzette, Luxembourg
[3]School of Psychology, University College Dublin, Dublin, Ireland

Corresponding author:
Fabiana Silva Ribeiro, Department of Social Sciences, University of Luxembourg, Belval Campus, 2, avenue de l'Université, L-4365 Esch-sur-Alzette, Luxembourg.
Email: fabiana.ribeiro@uni.lu

Working memory (WM) is crucial during learning processing as all new information needs to be processed within it (Lehmann & Seufert, 2017). According to Baddeley et al. (2012), WM is also responsible for evaluating and processing emotional information. In Baddeley's model, WM contains a component responsible for storing and integrating visuospatial information called the visuospatial sketchpad. In addition, this component is crucial for generating and manipulating mental images (Baddeley, 2007). Previous experimental studies have shown that visuospatial WM performance might be affected by a positive and negative mood or emotions evoked by varied types of induction procedures compared with the exposure to neutral stimuli (Allen et al., 2014; Gray, 2001; Palmiero et al., 2015, 2016; Ribeiro et al., 2019; Spachtholz et al., 2014; Storbeck & Maswood, 2016). However, others found no effect of affective stimuli on WM performance (Souza et al., 2021).

One source of confusion in the studies exploring emotions is the terminology adopted regarding affective terms, as they might not be interchangeable (Russell & Barrett, 1999). This study considers a concept of emotion based on Ekman's proposal, in which there are a limited number of primary emotions, such as fear, sadness, surprise, anger, joy, and disgust (Ekman, 1999). Emotions are subjective, intense reactions that arise in response to something experienced internally or externally by the subject, which is frequently described as an intentional and conscious experience (Beedie et al., 2005). In this approach, the influence of emotional stimuli seems to last from minutes to a few hours (Davidson et al., 2003).

Moreover, another source of misinterpretation in the results of studies exploring the effects of emotional stimuli is their impact depending on the location in the WM task (Ribeiro et al., 2019), for example, negative emotional stimuli used as a target in updating WM tasks were shown to increase scores compared with neutral target stimuli (Kensinger & Corkin, 2003; Pratto & John, 1991) as the processing of emotional stimuli seems to boost controlled attention (Pessoa, 2013; Vuilleumier & Huang, 2009). While positive and negative emotional induction prior to WM tasks seems to influence both storage and attentional processing associated with efficient WM functioning. Due to these possible differential effects regarding the positioning of the emotional stimuli in the WM task, in the following paragraphs, we summarize the main findings of those studies, including only emotional induction before the WM tasks as this was the design adopted in our experiment.

Studies have indicated that negative emotional induction could affect visual and visuospatial WM performance. For instance, Spachtholz et al. (2014) used a between-subjects design, in which one group of participants was allocated to an induction through negative autobiographical retrieval while listening to sad music, whereas the other group was exposed to the same type of neutral induction before performing a visual WM task. In their WM task, participants were required to remember a set of colored squares, and they found that participants remembered fewer colored squares after the negative induction than the neutral (Spachtholz et al., 2014). One explanation for this result seems to be associated with a different processing style and cognitive functioning when participants experience sad emotions compared with happy ones. In other words, emotions might influence the engagement of cognitive functioning, as well as possible brain regions, leading to gains or losses in performance.

In addition, a recent study (Souza et al., 2021) carried out five experiments using emotional images (negative, neutral, and positive), or one applying images combined with emotional music during a 3-min induction phase before each trial of a visual WM task involving a similar visual WM task used by Spachtholz et al. (2014). Although Souza et al. (2021) detected changes in participants' emotional states assessed by self-assessment manikin, they found no emotional induction effects on WM performance. However, the authors argued that their participants might not have experienced the emotions they reported, claiming the importance of taking a multimeasure approach, such as physiological responses, to validate participants' self-reported emotional state (Souza et al., 2021).

Furthermore, Allen et al. (2014) found a detrimental effect on a visuospatial WM storage task (Forward Block Recall) after inducing negative emotions by autobiographical retrieval compared with WM performance after neutral induction. In their experiments, Allen et al. (2014) used the supraspan method to measure WM performance in their experiments, composed of several trials. Specifically, they first defined each participant's span, which is the maximum sequence length of items they could store, using the Corsi task. Afterward, the authors tested participants using a WM task sequence length of the span plus two items in recall sequences containing 12 trials. Allen et al. (2014) claimed that this approach would be more sensitive to track the impact of emotional induction across trials, even if the emotional effects were transient. Congruently, their results showed a disruption caused by the induction, especially on the first trials of the task, which suggest that the impact of emotions induced by autobiographical memory seems to be transient or reduced by the attentional resources allocated to perform the WM task.

In general, Spachtholz et al. (2014) and Allen et al. (2014) attributed their findings to the reallocation of attention to aspects not related to the task at hand, consequently distracting attention away from task-appropriate processing (Ellis & Hertel, 1993). However, it is essential to point out that these studies did not assess the effect of positive valence on subsequent visuospatial WM tasks compared with a negative one to test whether the reallocation of attention would influence WM performance regardless of valence.

Regarding those investigations that explored the effects of positive, negative, and neutral states, two studies used video clips to evoke emotions, but with different WM tasks, such as two-back (Gray, 2001) and operation span (Storbeck & Maswood, 2016). Gray (2001) showed that visual WM was decreased due to positive evoked emotion, whereas the opposite occurred for negative emotion. These results were explained by the selective modulation of neural circuits in WM and emotion processing, which means that visual maintenance would be right-lateralized and positive emotions could lead to a greater left hemisphere activation, decreasing right hemisphere activations and consequently the WM performance, whereas the opposite would happen for negative emotion. In contrast, Gray (2001) and Storbeck and Maswood (2016) revealed that positive emotion enhanced WM. In contrast, a negative state did not influence performance and was comparable to the neutral one.

The source of discrepancy between the above-quoted studies, which used similar stimuli to induce emotions, could be explained by the different influences that positive and negative emotions seem to have on WM storage and processing. For instance, the two-back task would require more information storage than processing or executive control. However, the operation span requires much more executive control (Jaeggi et al., 2010). According to Storbeck and Maswood (2016), positive emotions might enhance executive control instead of short-term memory.

Two theories seem to explain the increasing effects of positive emotions on executive control: (1) the broaden-and-build theory, which posits that positive emotions can generate a broadened cognitive processing that enhances attention levels (Fredrickson, 2004) and (2) the dopaminergic theory claiming that positive emotions could enhance dopamine production leading to better management of executive control mechanisms (Ashby et al., 1999).

Regarding the effects of emotions evoked by music on WM tasks, a systematic literature review (Ribeiro et al., 2019) revealed that only two studies published by the same group

(Palmiero et al., 2015, 2016) investigated the impact of positive and negative music on WM performance of healthy participants, specifically on visuospatial WM capacity. Both investigations applied the Corsi block-tapping test and the walking Corsi test while participants listened to positive, negative, or neutral songs. Their results showed that only the positive emotion was effectively induced by comparing pre- and postemotional induction measurements. Positive induction resulted in increased WM scores compared with WM performance during negative induction and neutral state. The authors attributed their results to the arousal-mood hypothesis (Thompson et al., 2001), described below. Nevertheless, two major concerns regarding (Palmiero et al., 2015, 2016) were the use of a between-subjects design and the lack of a baseline WM performance before the emotional induction, which could be crucial to explain WM results.

The arousal-mood hypothesis (Nantais & Schellenberg, 1999; Thompson et al., 2001) was developed to explain the effects of musical emotions on cognitive tasks. According to Nantais and Schellenberg (1999), the impact of emotions evoked by music depends on three dimensions: the tempo (rhythm), mode (tone), and listeners' enjoyment (the pleasure felt while listening to music). Together, these three quoted dimensions could produce, in the case of a sad excerpt, a decrease in the efficiency of information processing (Srull & Wyer, 1989) and an increase of task-irrelevant thoughts leading to decrement in cognitive performance and learning, in contrast to happy excerpts (Nantais & Schellenberg, 1999).

Notwithstanding, according to Peterson et al. (2015), the assessment of emotions should consider self-reported emotions and physiological responses, in which the latter could show emotional intensity associated with the arousal levels (Rickard, 2004). Moreover, socially desirable answers do not influence psychophysiological measures (Paulhus, 2002). Although previous studies showed that physiology could be changed due to music listening, the findings are mixed. For instance, positive music produced greater skin conductance level (SCL) and heart rate (HR) than negative music (Fuentes-Sánchez et al., 2021; Khalfa et al., 2008; Krumhansl, 1997; Lundqvist et al., 2009). However, the experiment of Ribeiro et al. (2019) showed that both positive and negative emotional inductions through music (EIM) elicited increased SCL, and no results were observed for HR. Furthermore, in other studies, HR increased for both positive and negative stimuli compared with neutral music (Koelsch & Jäncke, 2015; Ogg et al., 2017).

This study aimed to explore further the impact of positive and negative emotions evoked through music on a WM performance comprising manipulation and storage of visuospatial information. In addition, arousal was measured through physiological measures (electrodermal and cardiac activities) to assess the electrophysiological correlates of a validated musical induction (Ribeiro et al., 2019). Moreover, we developed an adaptive visuospatial WM backward task to assess each participant in their maximum WM capacity, which allowed us to track the effects of EIM across trials using a within-subjects design. According to the arousal mood-hypothesis and the previous EIM studies, we expect to observe increased effects of positive EIM on WM performance compared with negative and neutral EIM, whereas negative EIM would decrease WM performance compared with the other EIMs. Moreover, as shown by Allen et al. (2014), we expected the effects of EIM on WM to be more pronounced in the first trials of the WM task due to the transitory emotional effect of EIM.

Regarding physiological responses, according to previous studies, it was predicted that positive and negative music would enhance SCL compared with neutral music. However, concerning HR, as former studies showed mixed results, we could expect different outcomes, such as higher HR for positive music compared with negative and neutral music, or increased HR for

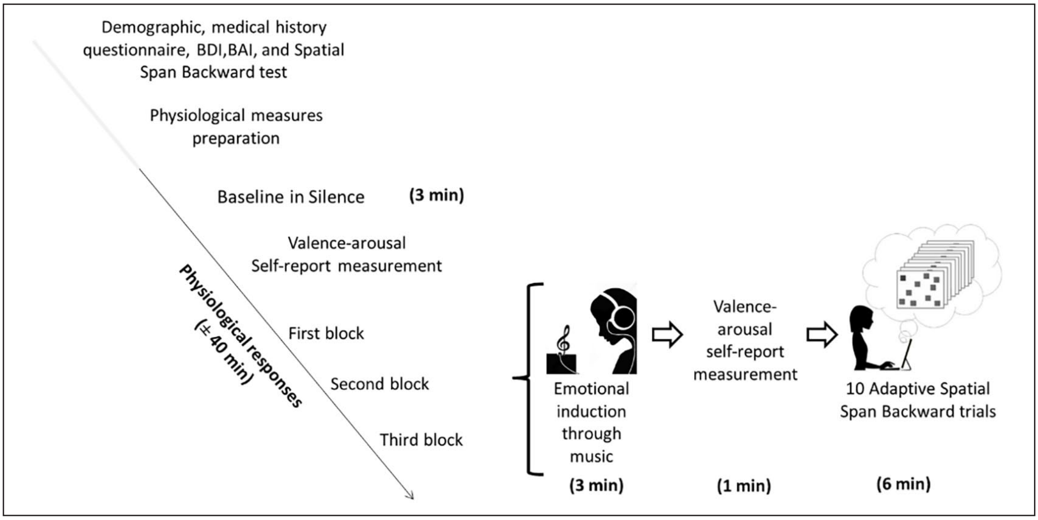

Figure 1. Scheme of the Experimental Procedure Including One of the Three Blocks.
BAI: Beck Anxiety Inventory; BDI: Beck Depression Inventory.

both positive and negative in comparison to neutral music, or no results as shown in a study with Portuguese population (Ribeiro et al., 2019).

Method

Participants

Ninety-five participants took part in this experiment. Seventeen participants were excluded from all analyses for the following reasons: five presented severe symptoms of self-reported anxiety or/and depression; eight participants were excluded because of procedural problems; and four because physiological data contained excessive recording artifacts.

Therefore, the final sample comprised 78 healthy participants (60 women and 18 men, $M_{age} = 23.76$, $SD_{age} = 5.27$). None of them were professional musicians, and all participants were Portuguese native speakers. All participants signed informed consent forms, and they voluntarily joined this study and received no payment.

Design

We applied a within-subject design in this experiment, with EIM having three levels: negative, positive, and neutral. The dependent variables were valence and arousal self-reported rates, visuospatial WM performance (adaptive spatial span backward trials), and physiological responses (SCL and HR activity) continuously recorded during the procedure. The order of the three EIMs was counterbalanced using a simple Latin square (negative–neutral–positive, neutral–positive-negative, or positive-negative–neutral). Each block comprised the EIM, valence-arousal measurement, and 10 adaptive spatial span backward (SSB) trials (see Figure 1). SCL and HR activity were recorded simultaneously throughout the experiment. In addition, we included 3 min of silence to capture baseline physiological activity to be compared with the three EIMs.

Materials

Screening measurements

Demographic and medical history questionnaire. Participants provided information regarding age, employment status, household incoming, and medical history.

Beck Anxiety Inventory. This self-report scale includes 21 questions that participants must rate from 0 (*not at all*) to 3 (*severely*; Beck & Steer, 1993), reflecting the participants' current anxiety level (adapted version for European Portuguese from Quintão et al., 2013; Cronbach's coefficient α was .79, is reasonably good).

Beck Depression Inventory. The Beck Depression Inventory (BDI) is a self-application instrument composed of 21 items in which participants must rate from 0 (*not at all*) to 4 (*severely*; Beck et al., 1996), with higher total scores designating more severe depressive symptoms (adapted version for European Portuguese from Campos and Gonçalves (2011). Cronbach's coefficient α was .90, classified as having adequate reliability].

Emotional induction through music. We selected the musical excerpts from a previous study that showed the efficacy of 3-min excerpts in eliciting emotional states in the Portuguese population (Ribeiro et al., 2019). Negative emotion was induced with Albinoni's *Adagio in G-minor* in triple meter, positive emotion with Bach's *Brandenburg Concerto No. 2*; finally, the neutral excerpt was *Variations for winds, strings, and keyboard* composed by Steve Reich.

Valence and arousal self-report measures. Participants were required to rate their emotional state on the valence dimension by selecting one out of nine adjectives that better represented how they felt while listening to the musical excerpts (adapted from Plutchik, 2001). There were three adjectives related to positive emotions (*happy*, *excited*, and *euphoric*), three to negative emotions (*sad*, *melancholic*, and *distressed*), each with low, medium, and high intensities, respectively, and three adjectives to rate neutral mood with the same value (*neutral*, *indifferent*, and *unresponsive*).[1] In line with the valence intensities, to further analyze self-reported valences, one corresponded to sad, two to melancholic, three to distressed, four to neutral, five to happy, six to excited, and seven to euphoric, all the adjectives were carefully tested and used to assess valence by previous studies (see Ribeiro et al., 2019; Soares, 2015; Souza et al., 2021).

The arousal dimension was measured immediately after valence, and participants were requested to rate the arousal on a 7-point analogic scale, in which 1 corresponded to *I feel very little arousal* and 7 to *I feel very much aroused.*

Preparation of valence and arousal self-report data. We calculated *change values* (CVs) for each EMI (positive, negative, and neutral) by subtracting the individual self-reported responses at baseline from each valence and arousal self-report after EIM.

Psychophysiological measures. We complemented emotional measurements with HR and SCL responses, which provide physiological arousal indexes (Fuentes-Sánchez et al., 2021). The HR and SCL channels were recorded at a sampling rate of 1,000 Hz, using BioPac Systems Inc. MP150 with the BN-PPGED and BN-RSPEC wireless BioNomadix amplifiers modules, respectively (BioPac Systems; Santa Barbara, CA, USA). The acquisition device was linked to a computer running AcqKnowledge software 4.4.

Skin conductance level. For the SCL, the disposable electrodes (BioPac Systems EL 507's) were attached to the palmar surface of the medial phalanges of the index and middle fingers of the nondominant hand. Posteriorly, the experimenter placed the BioNomadix transmitter on the participants' nondominant wrist. Then, the raw SCL data were filtered according to recommended procedures, specifically an FIR low-pass Blackman filter of 1 Hz with coefficients set at 4,000 (Coutinho et al., 2017).

Heart rate. The HR (bpm) was achieved from participants' raw electrocardiogram using an adjusted three-electrode Lead-II configuration. Before the placement of the disposable Ag–Ag-Cl electrodes, the skin was cleaned with alcohol and dried using a piece of cotton to improve signal quality and decrease impedance. Only then electrodes were placed on the participants' left acromial and sternal end of the clavicle, and a third one on the left spine of the scapula (BioPac Systems EL503's), and a transmitter belt was attached around participants' pectoral.

HR was calculated from the filtered using the following filter settings: an infinite impulse response (IIR) low-pass filter set at 35 Hz and IIR high-pass filter at 1 Hz (Coutinho et al., 2017); subsequently, the electrocardiogram trace was acquired from the filtered data using the Acknowledge 4.4 software.

Preparation of physiological data. We calculated 3-min epoch means (for each EIM) for each participant on SCL and HR responses from the filtered data and exported them to SPSS for further analysis.

Moreover, we also calculated the *CVs* to serve as dependent variables, in which we subtracted the baseline 3-min epoch mean from the 3-min epoch mean of each EIM) for each 3-min mean during EIM for each participant's SCL and HR responses. The CV establishes how much the physiological responses changed for each participant compared with their baseline.

Visuospatial WM task. We evaluated each participant's span visuospatial WM capacity by using the spatial span backward test, adapted for computerized presentation on a 17" Fujitsu L7ZA LCD computer screen, in which 10 blocks were placed at their relative standard positions as 10 blue squares (each 2.5 cm × 2.5 cm in size) on a white background. The block locations were consistent across participants and trials. This test began with a training phase, in which trials with three blocks (the "target") were highlighted in red for 1,000 ms one at a time before reverting to blue. After this, participants, using a mouse, were asked to click on the previously highlighted targets in the reverse order presented. If the participant's response was correct, they were invited to continue to the experimental phase; if not, they were required to do the training phase again. Feedback (i.e., correct or wrong response) was provided in both cases. The training phase lasted no longer than 30 s. The experimental phase was like the training phase but comprised two trials per length (between three and eight blocks as targets), no feedback was presented in this phase. The order of the highlighted blocks was computer-programmed by the experimenter and was different from trial to trial. The span was defined by the two correct trials at a given length.

The Adaptive SSB also included 10 blue blocks displayed on the computer screen as described before and comprised 10 randomized trials. Each trial had the maximum span capacity achieved by the participant in the SSB test.

Preparation of visuospatial WM data. The performance in the SSB was scored in two different ways, described as follows: First, we computed all-or-nothing scores, in which only corrected trials were considered, and second, we calculated partial-credit-scoring, in which we scored the percentage of correct locations in each trial.

The statistical analyses were carried out with the *total scores*, the sum of total trials correct per participant, and the mean total percentage of locations correct in each trial. Furthermore, to explore the temporal effects of EIM on the visuospatial performance, the performances were grouped into "first half trials" in which we added the correct trials or percentage of correct locations in the first five trials, and "second half trials," which were the sum or percentage of the five lasting trials.

Procedure

All the general information about the study was given to participants before being asked to sign a written consent form. Then, participants were screened with the demographic and medical history questionnaire, Beck Anxiety Inventory (BAI), and BDI. Subsequently, they performed the SSB span measurement to establish the length of the 10 sequences to be implemented in the Adaptive SSB task. Later, the electrodes were placed, and the physiological recording started. Subsequently, participants were asked to wait in silence for 3 min without musical presentation as we needed a baseline for the physiological responses. Afterward, participants were asked how they were feeling by choosing one of the nine adjectives displayed on the screen to assess emotional valence, and it was followed by a 1–7 analogous scale to assess arousal. Then, the initial EIM instruction was displayed on the computer screen, in which participants were instructed to close their eyes as they listened to the musical excerpt. Next, they proceeded to the first of the three EIMs. The musical excerpts were presented via headphones Sennheiser HD 202 II at a comfortable volume level (below 60 dB). The valence-arousal self-report followed each EIM and then the Adaptive SSB of 10 trials with each participant's maximum span capacity. Once they had completed the first block (EIM plus the Adaptive SSB trials), they were immediately induced successively for a second and third time with the same steps as described before. The conditions (positive, negative, and neutral) orders were counterbalanced across participants. The experiment was conducted individually and lasted approximately 40 min.

Statistical analyses

First, to investigate the efficacy of the EIMs, two independent one-way repeated-measures analyses of variance (ANOVAs) were performed to compare the effects of positive, negative, and neutral EIM on valence and arousal self-report CVs. Second, four separate one-way repeated-measures ANOVAs were carried out to compare, first, SCL, and second, the HR during baseline, positive, negative, and neutral EIM. Then, we performed similar analyses for SCL and HR CVs to explore whether EIMs could affect physiological responses in our sample. Regarding the WM performance, we conducted a repeated measure 3 (EIM: positive, negative, and neutral) $\times$ 2 (Time: the first half of trials and the second half of trials) multivariate analysis of variance (MANOVA) to explore whether EIM influenced visuospatial WM performance during the first five trials and the five last ones. We then conducted one-way repeated measures ANOVA to see whether EIM conditions could influence the total score of the 10 trials of the Adaptive SSB accuracy. Moreover, similar analyses were performed to explore the possible impact of the EIMs on the percentage of correct locations in the trials for each EIM. Finally, we conducted Pearson correlation analyses to explore whether physiological responses were related to changes in WM performance. The correlations were calculated among the WM scores and SCL and HR CVs.

Table 1. Means and Standard Deviations (in Parentheses) for Self-Reported Valence and Arousal.

Self-reports	Valence	Arousal	Valence change values	Arousal change values
Baseline	4.20 (.81)	4.63 (1.16)	–	–
Positive	5.10 (1.09)	4.70 (1.25)	.90 (1.40)	.07 (1.57)
Negative	3.05 (1.25)	4.24 (1.17)	−1.15 (1.26)	−1.19 (3.28)
Neutral	3.99 (1.68)	4.61 (0.99)	−.22 (1.80)	−.01 (1.27)

Results

Effectiveness of emotional inductions

The repeated measures ANOVA showed a significant effect of EIM on valence self-reported CV, $F(2, 154) = 50.64$, $p < .001$, $MSE = 1.62$, $\eta_p^2 = .40$. Paired sample *t*-tests with Bonferroni corrections revealed that the positive EIM CV was higher compared with the negative EIM ($p < .001$) and neutral EIM ($p < .001$), whereas the negative EIM CV was lower than neutral ($p < .001$). Table 1 shows the means and standard deviations for self-reported valence and arousal.

Furthermore, we also detected significant differences for arousal self-reported CVs, $F(2, 154) = 11.\ 35$, $p < .001$, $MSE = 3.45$, $\eta_p^2 = .13$. Arousal CV scores were higher for positive EIM than negative ($p < .001$). In contrast, negative EIM was lower compared with neutral EIM. Table 2 displays the paired sample *t*-test results for valence and arousal CVs.

Physiological measures

Two one-way repeated-measures ANOVAs were carried out to compare, first, SCL, and second, the HR during resting state, positive, negative, and neutral EIM. The first analyses revealed a significant effect on SCL, $F(3, 231) = 3.02$, $p = .03$, $MSE = .76$, $\eta_p^2 = .4$. As shown in Table 3, the paired *t*-test comparisons showed that SCLs increased from the baseline ($p = .01$).

A one-way repeated-measures ANOVA conducted for HR responses revealed significant differences during EIM and resting state, $F(3, 231) = 38.04$, $p < .001$, $MSE = 15.63$, $\eta_p^2 = .33$, where HR activity decreased during positive EIM compared with resting HR ($p < .001$). The mean and standard deviation of SCL and HR responses are reported in Table 4.

A one-way repeated-measures ANOVAs performed with SCL CVs did not reveal significant difference among groups, $F(2, 154) = .87$, $p = .42$, $MSE = .71$, $\eta_p^2 = .01$; however, we detected difference for CV HR, $F(2, 154) = 75.97$, $p < .001$, $MSE = .9.99$, $\eta_p^2 = .5$.

Visuospatial WM performance

The visuospatial span mean assessed by the SSB was 5.88 ($SD = 0.58$), so each sequence length of the Adaptive SSB trials ranged from five to seven span items. A 3 (EIM: positive, negative, and neutral) × 2 (Time: first half of trials and second half of trials) repeated measures MANOVA revealed a main effect of EIM, $F\ (2, 154) = 10.40$, $p < .001$, $MSE = 1.53$, $\eta_p^2 = .12$. However, there was no main effect of time, $F(1, 77) = 3.27$, $p = .07$, $MSE = .94$, $\eta_p^2 = .04$. Furthermore, we found an interaction between EIM and Time, $F(2, 154) = 4.37$, $p = .01$, $MSE = .88$, $\eta_p^2 = .05$. To disentangle this analysis, we performed paired sample *t*-tests and it was detected that the first half of trials were higher after positive EIM compared with negative ($p < .001$) and the neutral EIM total score ($p = .003$).

Table 2. Paired Sample *t*-Tests Comparing Valence and Arousal Self-Report CVs for Each EIM.

	Variables	*M*	*SD*	9 5% Confidence interval		*t*	*p*
				Lower	Upper		
Valence CVs							
Pair 1	ValenceCVpos—ValenceCVneg	2.05	1.78	1.65	2.45	10.18	<.001*
Pair 2	ValenceCVpos—ValenceCVneu	1.12	1.93	0.68	1.55	5.09	<.001*
Pair 3	ValenceCVneg—ValenceCVneu	−0.94	1.68	−1.31	−0.56	−4.90	<.001*
Arousal CVs							
Pair 1	ArousalCVpos—ArousalCVneg	1.27	2.97	0.60	1.94	3.78	<.001*
Pair 2	ArousalCVpos—ArousalCVneu	0.090	1.34	−0.21	0.39	0.59	.56
Pair 3	ArousalCVneg—ArousalCVneu	−1.18	3.18	−1.90	−0.46	−3.28	.002*

CV: change value; *SD*: standard deviation.
*Significance level of $p = .02$ (.05/3) with Bonferroni correction for multiple tests.

We then conducted one-way repeated-measures ANOVA to see whether EIM conditions could influence the total score of the 10 trials of the Adaptive SSB accuracy. This analysis showed a significant effect for EIM conditions on the total score of Adaptive SSB, $F(2, 154) = 10.40$, $p < .001$, $MSE = 3.07$, $\eta_p^2 = .12$. The total score was higher after positive EIM compared with negative ($p < .001$) and the neutral EIM total score ($p = .005$). See Figure 2 for the percentage of correct responses per trial after the EIM condition. Means and standard deviations are displayed in Table 5.

We also carried out a 3 (EIM: positive, negative, and neutral) × 2 (Time: first half of trials and second half of trials) repeated-measures MANOVA including the percentage of the correct locations in the trials. We found a main effect of EIM, $F(2, 154) = 4.47$, $p < .01$, $MSE = 173.22$, $\eta_p^2 = .06$. However, there was no main effect of time, $F(1, 77) = .36$, $p = .55$, $MSE = 170.73$, $\eta_p^2 = .005$. Furthermore, we found an interaction between EIM and Time, $F(2, 154) = 6.14$, $p = .003$, $MSE = 115.52$, $\eta_p^2 = .07$. Paired sample *t*-tests revealed that the first half of trials were higher after positive EIM compared with negative ($p < .001$) and the neutral EIM total score ($p = .006$).

We also detected significant results for repeated-measures ANOVA for the total percentage of correct locations, $F(2, 154) = 4.46$, $p = .01$, $MSE = 86.66$, $\eta_p^2 = .05$, in which performance was higher after positive EIM compared with negative ($p = .009$). All the paired *t*-tests results are displayed in Table 6. Moreover, in Supplementary Materials online, we included a Table S1 comprising the mean percentages and standard deviations of correct locations in each trial and the sum of correct responses.

Correlations

Pearson correlations showed positive and significant correlations for SCL responses for the percentage of correct locations at the first half of trials after positive EIM, $r = .20$, $p = .03$. We also detected that the second half trial of the percentage of correct locations was associated with SCL neutral, $r = .20$, $p = .04$. Finally, the first half of trials, including correct trials after negative EIM, was positively associated with SCL CV during negative EIM, $r = .22$, $p = .02$, and HR CV during negative EIM, $r = .24$, $p = .01$.

Table 3. Paired Sample *t*-Test Comparing SCL and HR Responses for Each EIM.

	Variables	*M*	*SD*	95% confidence interval		*t*	*p*
				Lower	Upper		
SCL							
Pair 1	Baseline SCL—SCL pos	−0.40	1.34	−0.71	−0.10	−2.66	.01*
Pair 2	BaselineSCL—SCL neg	−0.30	1.21	−0.58	−0.03	−2.20	.03
Pair 3	BaselineSCL—SCL neu	−0.23	1.25	−0.51	0.06	−1.59	.12
HR							
Pair 1	BaselineHR—HRpos	5.72	7.09	4.12	7.32	7.12	<.001*
Pair 2	BaselineHR—HRneg	0.56	6.21	−0.85	1.96	0.79	.43
Pair 3	BaselineHR—HRneutra	0.11	6.21	−1.29	1.51	0.15	.88
SCL-CV							
Pair 1	SCL-CVpos—SCL-CVneg	0.10	1.25	−0.18	0.38	0.71	.48
Pair 2	SCL-CVpos—SCL-CVneu	0.18	1.06	−0.06	0.42	1.48	.14
Pair 3	SCL-CVneg—SCL-CVneu	0.08	1.26	−0.21	0.36	0.54	.59
HR-CV							
Pair 1	HR-CVpos—HR-CVneg	−5.17	5.11	−6.32	−4.01	−8.92	<.001*
Pair 2	HR-CVpos—HR-CVneu	−5.61	4.95	−6.73	−4.50	−10.02	<.001*
Pair 3	HR-CVneg—HR-CVneu	−0.45	3.05	−1.14	0.24	−1.30	.20

CV: change value; HR: heart rate; SCL: skin conductance level; *SD*: standard deviation.
*Significance level of $p = .02$ (.05/3) with Bonferroni correction for multiple tests.

Table 4. Means and Standard Deviations (in Parentheses) for SCL and HR Pre and After EIM Conditions.

Physiological responses	SCL $_{(\mu S)}$	HR $_{(bpm)}$	SCL$_{(\mu S)}$ CV	HR $_{(bpm)}$ CV
Baseline	4.12 (2.24)	80.20 (12.31)	–	–
Positive	4.52 (2.60)	74.48 (11.77)	0.40 (1.34)	−5.72 (7.09)
Negative	4.42 (2.63)	79.65 (11.96)	0.30 (1.21)	−0.56 (6.21)
Neutral	4.35 (2.57)	80.10 (11.47)	0.23 (1.25)	−0.11 (1.57)

SCL: skin conductance level; HR: heart rate.

Discussion

The present study explored the effects of positive, negative, and neutral EIMs on subsequent visuospatial WM performance. Our results revealed an increased effect of the positive EIM on subsequent visuospatial WM processing performance, in both computed scores for correct trials and percentage of correct locations in the trials, compared with negative and neutral EIM, congruent with our first hypothesis and previous studies (Palmiero et al., 2015, 2016). However, although our procedure seemed to be effective in promoting positive and negative emotions, as well as a neutral state according to self-reported valence rates, no decrease in WM performance was observed for the negative EIM compared with neutral EIM, as we predicted (Allen et al., 2014; Ribeiro et al., 2019; Souza et al., 2021; Spachtholz et al., 2014).

At first glance, our results seem to reinforce the findings achieved by Storbeck and Maswood (2016), showing that neither negative nor neutral EIM has effects on visuospatial WM

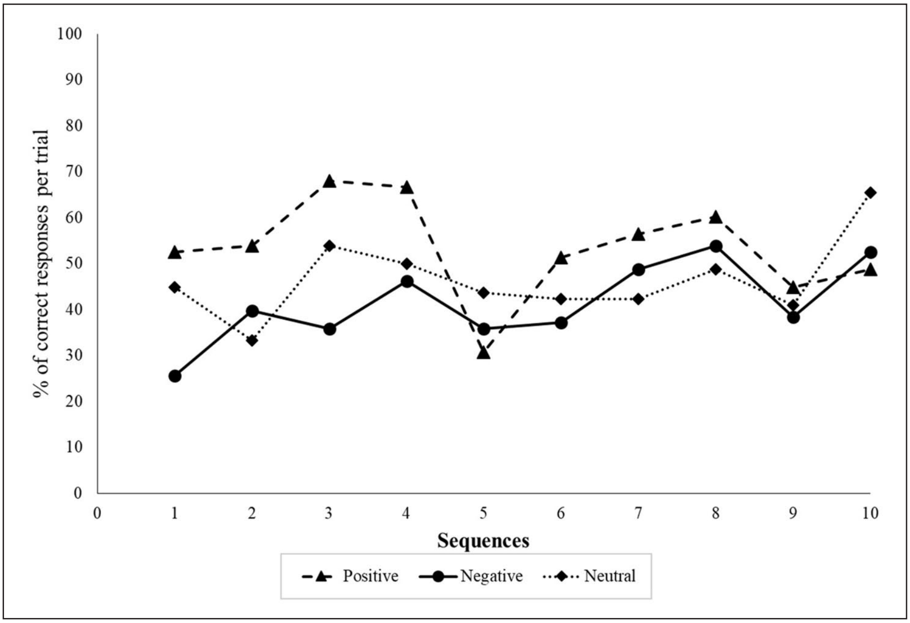

Figure 2. Percentage of Correct Responses Per Trial on Adaptive SSB after Each EIM Condition.

Table 5. Means and Standard Deviations (in Parenthesis) for Correct Trials in the Five First Trials and Last Ones, and Total Score of Adaptive SSB, According to EIM Condition.

Correct trials	Sum of the first half trials	Sum of the second half trials	Total
Positive EIM	2.59 (1.62)	2.11 (1.58)	4.70 (2.85)
Negative EIM	1.64 (1.63)	1.79 (1.65)	3.50 (3.07)
Neutral EIM	2.05 (1.59)	1.88 (1.41)	3.93 (2.73)
Percentage of correct locations			
Positive EIM	76.79 (19.49)	71.52 (20.57)	74.15 (18.23)
Negative EIM	68.15 (19.99)	71.34 (19.53)	69.74 (18.26)
Neutral EIM	71.45 (19.61)	71.35 (18.18)	71.40 (16.84)

EIM: emotional induction through music.

processing. Nevertheless, we observed that negative EIM was not effective in inducing lower arousal levels compared with neutral EIM, assessed either by self-report or physiological responses, as we expected (Nantais & Schellenberg, 1999; Thompson et al., 2001), which might indicate that valence by itself is not sufficient to influence high-demanding WM performance.

By carefully analyzing the data coming from both self-report and physiological measurements, the first detected higher arousal for positive EIM than negative EIM CVs and lower arousal for negative EIM CVs compared with neutral EIM. Whereas the second showed that only the positive induction promoted increased SCL compared with its baseline. In contrast, HR for positive EIM was decreased, and lower HR during positive EIM CVs compared with negative and neutral EIMs. One explanation for the incongruence in the self-report arousal-related and

Table 6. Paired Sample *t*-Tests Comparing WM Performance for Each EIM.

	Variables	*M*	*SD*	95% Confidence Interval		t	*p*
				Lower	Upper		
Total of correct trials							
Pair 1	Positive—negative	1.21	2.56	0.63	1.78	4.16	<.001*
Pair 2	Positive—neutral	0.77	2.34	0.24	1.30	2.91	.005*
Pair 3	Neutral—negative	0.44	2.54	−0.14	1.01	1.52	.13
Total percentage of correct locations							
Pair 1	Positive—negative	4.41	14.45	1.15	7.66	2.69	.009*
Pair 2	Positive—neutral	2.75	12.86	−0.15	5.65	1.89	.06
Pair 3	Neutral—negative	1.66	12.07	−1.06	4.38	1.21	.23
Correct trials by the first half and the second half							
Pair 1—first half	Positive—negative	0.95	1.57	0.59	1.30	5.34	<.001**
Pair 2—first half	Positive—neutral	0.54	1.54	0.19	0.89	3.08	.003**
Pair 3—first half	Neutral—negative	0.41	1.73	0.02	0.80	2.09	.04
Pair 4—second half	Positive—negative	0.32	1.57	−0.03	0.67	1.80	.08
Pair 5—second half	Positive—neutral	0.23	1.47	−0.10	0.56	1.39	.17
Pair 6—second half	Neutral—negative	−0.09	1.42	−0.41	0.23	−0.56	.58
Total percentage of correct locations in the first half and the second half							
Pair 1—first half	Positive—negative	8.64	17.69	4.65	12.63	4.31	<.001**
Pair 2—first half	Positive—neutral	5.34	16.81	1.54	9.12	2.80	.006**
Pair 3—first half	Neutral—negative	3.31	18.35	−0.83	7.44	1.59	.11
Pair 4—second half	Positive—negative	.18	18.04	−3.89	4.25	0.09	.93
Pair 5—second half	Positive—neutral	0.16	16.24	−3.50	3.83	0.089	.93
Pair 6—second half	Neutral—negative	0.01	14.51	−3.26	3.29	0.009	.99

SD: standard deviation.
*Significance level of $p = .02$ (.05/3) with Bonferroni correction for multiple tests.
**Significance level of $p = .008$ (.05/6) with Bonferroni correction for multiple tests.

physiological results could be that emotions might communicate directly with sense organs and the brain, resulting in individuals not consciously recognizing or reporting the emotional response clearly (LeDoux, 1998). Thus, self-report measures may result in the omission of valuable arousal-related information. Importantly, we observed the associations of physiological responses to some of the WM scores computed, which indicates an influence of EIM on the WM task. Furthermore, all these results showed the importance of including physiological measures to assess arousal indexes effectively.

Although previous studies quite well established the influence of negative music on the valence and arousal level, caution is needed when negative musical stimuli are chosen. So far, it is unclear which variables are responsible for these mixed findings. Moreover, future studies should also test music chosen by the participants since it seems to be more effective in inducing arousal compared with music selected by the experimenter (Völker, 2019).

Regarding our second hypothesis related to the transitory emotional effect of EIM on WM performance trials, we detected indeed a transient impact of positive emotion affecting the first trials of the Adaptive SSB WM task significantly, and this indicates the temporal decrease in the intensity of the emotional state 3 min after the induction (Ribeiro et al., 2019).

Our findings contrast with the literature that showed that positive induction could also decrease WM performance (Allen et al., 2014; Ellis & Hertel, 1993). However, different emotional induction procedures may overload the WM processing differently; for instance, the evocation and maintenance of autobiographical memories independent of its valence seem to generate overloads of information on WM storage and processing neutral autobiographical memories (Allen et al., 2014). Furthermore, in their study, emotions were elicited through endogenous stimuli, which might have, due to their familiarity, a stronger emotional impact on participants than exogenous stimuli, such as the musical excerpts.

Additionally, the effects of positive EIM can be explained by increased dopamine levels (Ashby et al., 1999), which can broaden the cognitive processing and thinking style associated with higher attention levels, exploratory thoughts, and actions (Fredrickson, 2004). In congruence, we found decreased HR responses only for positive EIM, which suggest a higher mental functioning that might have influenced the first trials after positive EIM (Scholey et al., 1999).

In conclusion, our results suggest that positive music's emotions might increase executive control/processing scope and improve WM capacity transiently. Furthermore, our results indicate that the musical effect on subsequent visuospatial WM tasks might depend on valence and arousal conjunctly. It is essential to point out that this study is one of the first to investigate the effects of EIM on visuospatial WM tasks, using a within-subjects design, simultaneously registering physiological responses. For this reason, more studies should be carried out to clarify the effects of negative EIM and also on diverse WM task performance.

Some limitations and future directions should be mentioned. Although we were able to capture arousal levels with physiological responses, one of the limitations of this study concern the valence and arousal self-report assessment (Ribeiro et al., 2019; Soares, 2015; Souza et al., 2021) as it does not capture a broad level of arousal responses, for instance, relaxed levels. In this context, future studies should consider other self-reporting methods, such as the self-assessment manikin (Bradley & Lang, 1994; Lang, 1980).

A second limitation of this study was the use of a fixed individualized span as it could be wrong at the first assessment making the following measurement less reliable. However, looking carefully at the data of all included participants, it is not possible to observe ceiling effects or incorrect answers in all the trials, which reveals that at least in the included sample, the SSB test was effective in detecting the span capacity of participants. Finally, although the task used in this study included processing and storing information, our task did not provide specialized scores. Therefore, future studies should investigate the impact of emotional induction in the processing and storing information separately.

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ORCID iD

Fabiana Silva Ribeiro https://orcid.org/0000-0003-1826-5253

Supplemental material

Supplemental material for this article is available online.

Note

1. Portuguese words for positive (*Feliz*, *entusiasmado*, and *Eufórico*), negative (*Triste*, *melancólico*, and *angustiado*), and neutral (*Neutro*, *alheio*, and *indiferente*) self-report mood.

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