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The effect of post-learning presentation of music on long-term word-list retention

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ABSTRACT

Memory consolidation processes occur slowly over time, allowing recently formed memories to be altered soon after acquisition. Although post-learning arousal treatments have been found to modulate memory consolidation, examination of the temporal parameters of these effects in humans has been limited. In the current study, 127 participants learned a neutral word list and were exposed to either a positively or negatively arousing musical piece following delays of 0, 20 or 45 min. One-week later, participants completed a long-term memory recognition test, followed by Carver and White's (1994) approach/avoidance personality scales. Retention was significantly enhanced, regardless of valence, when the emotion manipulation occurred at 20 min, but not immediately or 45 min, post-learning. Further, the 20 min interval effect was found to be moderated by high 'drive' approach sensitivity. The selective facilitatory conditions of music identified in the current study (timing and personality) offer valuable insights for future development of more specified memory intervention strategies.

1. Introduction

Privileged memory for emotional events relative to non-emotional events has been extensively documented (Cahill & McGaugh, 1995; Hamann, Ely, Grafton, & Kilts, 1999; McGaugh, 2000; Sharot & Phelps, 2004). Despite enduring controversy, the emotional arousal hypothesis has provided a compelling theoretical account (Liu, Graham, & Zorawski, 2008). A central feature of this thesis is that emotional memory enhancement operates via a narrow temporal window of arousal facilitation (Nielson & Powless, 2007). As a potent source of emotional arousal, music exposure might conceivably form a powerful exogenous means of memory modulation (Berlyne, 1971; Krumhansl, 1997).

According to the emotional arousal hypothesis, perception of an event as significant stimulates concomitant activation of neural and physiological systems, including the release of various adrenal stress hormones into the bloodstream (i.e., epinephrine, norepinephrine, and cortisol) (Cahill & McGaugh, 1998; Gibbs & Summers, 2002; McGaugh, 2000, 2004). These mechanisms have been closely linked to the modulation of recently acquired information, and subsequent enhancement of emotional memory (McGaugh, 2000).

Although emotional events are exemplified by a coincident arousal onset, the effects of arousal are also enduring for some time afterward (Nielson, Yee, & Erickson, 2005). Therefore, in addition to having an influential capacity on attention and learning processes, physiological effects of emotional arousal can also extend to the memory consolidation phase (Nielson & Powless, 2007; Nielson et al., 2005). Memory consolidation is the product of complex neurobiological processes that occur over time (Cahill & McGaugh, 1998; McGaugh, 1966; McGaugh & Herz, 1972; Phelps, 2006). Significantly, the implicated foundational processes are dynamic and sensitive to both exogenous and endogenous influences (i.e., pharmacological and physical intervention, as well as arousal hormones; Cahill & McGaugh, 1998; Gibbs, 1991; Gold, 2004). As such, events which occur during or soon after learning can strengthen or weaken consolidation of the initially labile memory trace, a process known as 'neuromodulation' (Cahill & McGaugh, 1998; Gibbs, 1991; McGaugh, 2003).

A prevailing critique of most laboratory-based emotional memory studies involving human participants concerns the introduction of arousal-inducing stimuli prior to, or intrinsic to, the learning material (Cahill & McGaugh, 1995; Cahill, Prins, Weber, & McGaugh, 1994; Heuer & Reisberg, 1990; Quevedo et al., 2003). In particular, the capacity for arousal to influence attention and learning makes it difficult to distinguish such effects from those specific to memory consolidation (Cahill & McGaugh, 1995). The use of post-learning arousal treatments or manipulations provides a highly effective means of isolating memory consolidation effects independent of those operating on attention and learning processes (Nielson & Powless, 2007; Nielson et al., 2005).

The examination of time-dependent arousal facilitation effects on memory has almost exclusively been confined to animal paradigms, which typically foster a more rigorous and systematic experimental design with clear temporal parameters (Gibbs, 1991). Utilizing post-learning experimental procedures, the

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efficacy of arousal treatments on memory has been found to diminish with time, such that they are most effective when administered soon after learning (Gold & van Buskirk, 1975; McGaugh, 2000). Despite marginal discrepancies, when considered together the main body of findings subscribe to the general conclusion that arousal induced soon (possibly immediately) after learning, with an upper-most limit of 25 min post-learning, form the optimal temporal parameters of memory enhancement, at least within the animal models investigated (Crowe, Ng, & Gibbs, 1990; Gibbs & Summers, 2002; Gold & van Buskirk, 1978; McGaugh, 1983).

Nevertheless, the few studies that have examined post-learning arousal effects on memory consolidation have, predominately employed aversive stimuli or treatments (Cahill & McGaugh, 1995; Gibbs, 1991; Nielson et al., 2005). It is therefore possible that enhanced memory may reflect a generalised negative recall bias, rather than an arousal facilitation effect (Liu et al., 2008). In this regard, the findings of Nielson and Powless (2007) are significant, in that they recently demonstrated a capacity for both positive and negative sources of emotional arousal to influence memory consolidation in human participants. Participants learned a series of neutral words, followed by a pleasantly or aversively arousing film excerpt after delays of 0, 10, 30 or 45 min. Recall of word list items, assessed one-week later, was significantly enhanced for both pleasant and aversive arousal conditions relative to the no film control group, when the arousal manipulation was introduced any time up to 30 min, but not at 45 min post-learning. Similar observations of memory facilitation for both positively and negatively valenced stimuli suggest that emotional arousal rather than valence underlies this effect.

Music has been identified as a powerful medium with both arousal potential and emotion-inducing capacity (Berlyne, 1971). Moreover, affective states induced through music have been found to be stronger than affective states induced through other modalities, such as slide and narrative stimuli (Berlyne, 1971; Krumhansl, 1997; Rickard, 2004). With an extensive body of previous literature supporting the potential for music to increase and decrease arousal levels (e.g. Baumgartner, Esslen, & Jäncke, 2006; Taylor, 1973; VanderArk & Ely, 1992), it appears reasonable to speculate that music might have an intrinsic capacity to modulate memory consolidation.

Although there is supporting evidence for the potency of music as an agent of emotional arousal, the existing human literature is quite inconsistent (Rickard, Toukhsati, & Field, 2005). Numerous intra-personal variables have been found to moderate the nature and magnitude of musical reactivity (Berlyne, 1971; Hamann & Canli, 2004; Iwanaga & Moroki, 1999; Iwanaga & Tsukamoto, 1997; Kreutz, Ott, Teichmann, Osawa, & Vaitl, 2008; VanderArk & Ely, 1992). Dispositional factors such as personality type form a primary example (Furnham & Allass, 1999; Furnham & Bradley, 1997). With reference to the neuromodulation theory, physiological-based models of personality provide a useful framework for empirical investigation of arousal manipulation effects on memory (Eysenck, 1967; Gray, 1991).

A contemporary elaboration of Eysenck's (1967) traditional theory of personality is Gray's (1991) Behavioural Inhibition System/Behavioural Approach System (BIS/BAS) model. The BIS/BAS dichotomy represents independent neural motivation systems which govern behaviour and affect (Gray, 1991). The BIS principally regulates aversive motivation, and responds to aversive cues via behavioural inhibition, increased arousal, focused attention, and a proneness to experience negative affect (Gray, 1991). The BAS differentially regulates appetitive motivation, and is sensitive to signals of potential reward and non-punishment, by activating approach behaviour, namely increasing arousal, and directing attention toward positive stimuli. Greater BAS sensitivity is also associated with a tendency to experience positive affect for appetitive cues (Gray, 1991). In light of these characteristics, it is conceivable that the dispositional BIS and BAS sensitivities might moderate emotion-induction receptivity to highly arousing music of both positive (happy) and negative (fearful) valence.

The principal role of neuromodulation in the consolidation of LTM, coupled with the intrinsic arousal potential of music, underscores the possibility that music might represent a powerful exogenous means of memory modulation. Indeed, the use of music as a therapeutic medium in both clinical and specialist education settings is appealing because it is non-invasive, economical and has low risk of side effects (Batt-Rawden, 2007; White, 2001). Nevertheless, to cultivate efficient therapeutic application, it is important to determine the conditions under which music will be effective, including the temporal window within which memory consolidation is susceptible to enhancement. In this endeavour, post-learning arousal manipulations are advantageous as memory consolidation effects can be aptly demarcated. Further, presentation of both positively and negatively valenced stimuli allows for observation of legitimate arousal facilitation effects.

A modified version of the experimental methodology introduced by Nielson and Powless (2007) was adopted to examine the post-learning effects of music exposure (positively and negatively valenced) on memory consolidation. A secondary level aim was to examine whether any observed effects were moderated by dispositional BIS and BAS sensitivities. It was hypothesised that music of either valence (positive or negative) occurring up to 20 min, but not at 45 min following learning of a neutral word list, would enhance long-term word-list retention. It was also hypothesised that the effect of music on long-term retention would be moderated by BIS/BAS sensitivity, with stronger effects observed for participants high on each of the BAS scales, and low on the BIS scale.

1.1. Method

1.1.1. Participants

The total sample comprised 156 naive participants recruited through means of convenience sampling, poster advertisements and from the undergraduate Psychology Student pool. There were 123 female and 33 male participants within an age range of 18–59 years ($M = 25.04$, $SD = 8.41$). Participant exclusion criteria included stimulant consumption less than 2 h before participation, as well as uncorrected hearing impairment. Further, persons who anticipated distress from exposure to unpleasant music were advised not to participate in the study.

As a result of preliminary exclusion procedures, the overall sample size was reduced to $N = 127$. The amended sample comprised 103 female and 24 male participants within an age range of 18–59 years ($M = 24.64$, $SD = 8.00$). Participants were randomly assigned to one of seven experimental conditions, namely high arousal/positive valence music: 0 ($n = 19$), 20 ($n = 14$), or 45 ($n = 16$) min post-learning; high arousal/negative valence music: 0 ($n = 19$), 20 ($n = 18$), or 45 ($n = 20$) min post-learning; or no music control group ($n = 21$).

1.1.2. Materials

The present study was an on-line, music-oriented adaptation of the methodological procedures previously employed by Nielson and Powless (2007). Participants were required to create a unique password to ensure that responses from Session 1 and Session 2 were appropriately matched. A 5-item demographic survey was utilized to record gender and age of participants, recent stimulant consumption, as well as current mood and arousal levels. Respondents rated each item using independent Likert-type scales, with the exception of the age item which utilized a drop down selection box.

Thirty word list items (nouns) which featured in Nielson and Powless' (2007) study were also employed. To equilibrate memorability, each word was highly imaginable (above 6.0 on a scale ranging from 1to 7) e.g., "butterfly", "grass", and "house" (Paivio, Yuille, & Madigan, 1968). The 30 words were presented sequentially using white letters on a dark blue background, at 2 s intervals with no inter-stimulus delay. Of the 30 words used, 19 had standardized arousal and valence values, falling in the low-moderate arousal and moderate valence range (9-point scale, arousal $M = 4.65$, $SD = 0.81$; valence $M = 5.91$, $SD = 1.6$) (Bradley & Lang, 1999).

The emotional arousal conditions were manipulated using arousing stimuli from the classical genre music. Beethoven's *Symphony No. 6 (3rd mvt.)* was employed as the positive valence music excerpt and Modest Mussorgsky's *Night on bare mountain* was utilized as the negative valence piece. These pieces were selected following a pilot study in which 10 musical compositions (5 positive and 5 negative) sourced from past research (Baumgartner et al., 2006; Iwanaga & Tsukamoto, 1997; Krumhansl, 1997; Taylor, 1973; VanderArk & Ely, 1992, 1993) were each evaluated on arousal and valence, and familiarity and likability on independent Likert-type scales. The pieces for the main study were selected on the basis that they were the most arousing, negatively and positively rated pieces that were also rated similarly on familiarity and liking ratings (see Table 1). Previous research confirmed that the selected pieces have been found to be both physiologically arousing (as assessed by cardiac indices, respiration rate and skin temperature) and subjectively arousing (Baumgartner et al., 2006; Krumhansl, 1997). Both pieces were equalised on peak loudness, and were faded out gradually at a duration interval of approximately 3 min.

A variety of questionnaires was employed as fillers during the arousal manipulation delay intervals. These measures comprised the Positive and Negative Affect Scale (PANAS), Intelligence Type Test, Short Test of Music Preferences – Revised (STOMP – Revised), Brief Music Experience Questionnaire (BMEQ), and the Modified Tellegen Absorption Scale (MODTAS). All fillers contributed to an 'intelligence type' (that is, emotional, musical, verbal and so on) experimental ruse, and were fairly neutral in content. A post-intervention survey assessed participants' familiarity and liking of the musical stimuli, using independent Likert-type scales. Additionally, music arousal and valence were evaluated as a verification of manipulation using independent 7-point sliding scales ranging from "calm" to "excited" and "pleasant" to "unpleasant" respectively. A fatigue item was also presented using a 5-point Likert-type scale, where 1 = 'very tired' and 5 = 'very awake', to test the impact of this potential confound across conditions.

A 140-item LTM recognition test assessed recall of the word list items (Nielson & Powless, 2007). The LTM test consisted of the 30 original word list items, as well as 110 distracter words which used the same selection criteria as the target list. The LTM test was presented in five columns of 28 words, and each item was accompanied by a selection/check box.

Dispositional BIS and BAS sensitivities were assessed using the BIS/BAS scales developed by Carver and White (1994). The BIS scale comprises 7 items and provides an overall measure of BIS sensitivity. The BAS scale differentially comprises three subscales: BAS drive (4 items) reflects persistent pursuit of appetitive goals; BAS reward-responsiveness (5 items) reflects the tendency to respond positively to potential reward; and BAS fun-seeking (4 items) reflects the tendency to seek out and engage in activities of potential reward. Respondents used a 4-point Likert-type scale to rate each item, where 1 = 'very true for me' and 4 = 'very false for me'. The psychometric properties of the instrument have been shown to be acceptable, with alpha coefficients ranging from .66 to .76 (Carver & White, 1994).

1.1.3. Procedure

All procedures in the present study were approved by the Monash University Standing Committee on Ethics in Research Involving Humans (SCERH). Participants were not informed that the study would involve a LTM test, as intensive rehearsal of information can bias normal memory formation (Greene, 1987). Nonetheless, participants were generally informed that memory ability would be assessed, with an immediate free recall test meeting such expectations. Further, to de-emphasise the genuine LTM focus of the study, it was explained that the relationship between dominant intelligence type and gender formed the primary area of inquiry. On-line consent was subsequently obtained.

Participants created and confirmed their on-line password, and completed the demographics survey. Participants were then instructed to put on their headphones, and to keep them on for the duration of the session. A sample sound was presented, and through use of a sliding scale, volume was adjusted to a comfortable level for each participant. Participants were instructed to attend closely to the computer screen, and to repeat silently and try to remember the forthcoming word list items. The 30-item word list was then presented, followed immediately by a free recall test. Participants were allowed 3 min to recall as many words as possible by typing their responses into an open comments box, and they were informed not to worry about spelling mistakes.

The web experimental procedure randomly assigned participants to one of the seven experimental conditions. During delay intervals, participants completed the filler questionnaires. Where filler questionnaires were completed prior to the set time of the music-arousal manipulation, additional open-ended filler items were presented. Conversely, where participants did not complete the filler questionnaires prior to the music-arousal manipulation, unanswered items were presented for completion following music exposure. The post-intervention survey which included familiarity,

Table 1
Mean ratings for pilot study's music pieces, including selections in bold (Beethoven, Mussorgsky) for main study (standard deviations in brackets).

Piece	Arousal (1–7)	Valence (1–7)	Familiarity (1–5)	Liking (1–5)
		Negative pieces		
Penderecki: *Threnody for the victims of Hiroshima*	6.10 (0.55)	1.65 (1.14)	1.20 (0.41)	1.75 (0.55)
Mussorgsky: *Night on Bare Mountain*	**5.65 (0.59)**	**2.30 (0.86)**	**1.10 (0.31)**	**2.35 (0.59)**
Stravinsky: *Sacrificial Dance*	5.60 (0.60)	2.30 (0.47)	2.35 (1.31)	2.55 (0.51)
Shostakovich: (Adagio)	5.45 (0.60)	2.30 (0.47)	1.35 (0.59)	2.50 (0.51)
Holst: *Mars – the Bringer of War*	4.55 (0.69)	3.40 (0.68)	1.45 (0.76)	2.85 (0.37)
		Positive pieces		
Alfven: *Midsommarvaka*	4.00 (0.73)	4.25 (0.72)	1.65 (0.81)	3.05 (0.22)
Holst: *Jupiter*	5.10 (0.31)	5.00 (0.46)	1.60 (0.82)	3.20 (0.62)
Liszt: *Battle of the huns*	5.85 (0.59)	6.10 (0.55)	1.10 (0.45)	3.60 (0.50)
Beethoven: *Symphony No. 6 (3rd mvt.)*	**6.00 (0.65)**	**6.25 (0.55)**	**1.05 (0.22)**	**3.75 (0.97)**
Vivaldi: *La Primavera (Spring)*	6.35 (0.49)	6.60 (0.50)	4.75 (0.91)	4.30 (0.47)

likability, music arousal, and music valence items were completed immediately after the music was presented. Participants then indicated their level of fatigue.

Participants were invited to provide their email address to receive a reminder for Session 2 of the study, to be completed one-week later. To minimize the attrition rate from Session 1 to Session 2, participants were informed that completion of all study procedures conferred eligibility for a prize draw of two premium movie tickets, as well as a report on their dominant intelligence type. One-week later, participants accessed the experimental web page to complete Session 2. The surprise LTM recognition test was presented and participants were instructed to select all items they believed were from the original word list. One point was deducted for each incorrect response, because the methodology did not allow a false hit rate to be calculated. There were no imposed time constraints. The BIS and BAS scales were then completed. Participants were debriefed at the conclusion of the study, and were informed of the reason for use of mild deception.

1.2. Results

This study conformed to a 3 (interval of music manipulation: 10, 20 or 45 min post-learning) × 2 (music valence: positive or negative) independent measures factorial design. The control group was not exposed to any musical stimuli, providing a baseline mean against which memory recognition data from the six groups of interest was compared. The primary dependent variable was LTM recognition scores for word list items, measured as the sum of correct responses.

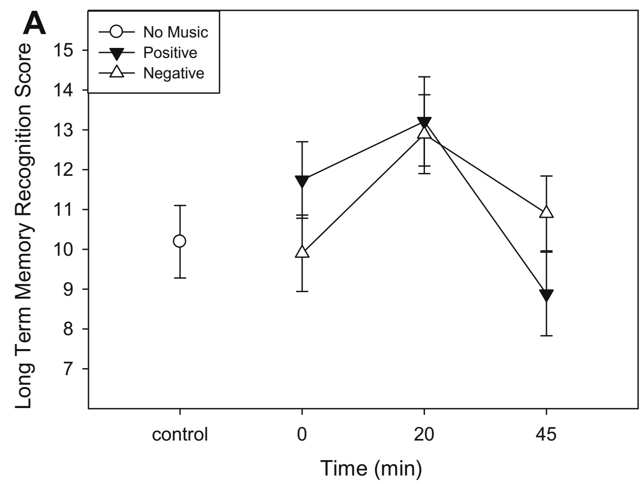
1.2.1. Data handling

Following reverse scoring of appropriate items, all questionnaires were scored according to their respective subscales. Analyses using the *Statistical Package for the Social Sciences (SPSS 17.0)* were then conducted. Preliminary data cleaning procedures revealed that of the original sample (N = 156), 17 participants did not complete Session 2. Their data were excluded from subsequent analyses. Further, 12 participants who reported consumption of stimulants within 2 h of the experiment onset were also excluded.

Exploratory analyses for the purposes of verifying the efficacy of the experimental manipulation, as well as various checks of potential confounds were performed on self-reported music arousal, music valence (single-sample t-tests), initial arousal, initial mood, fatigue (one-way independent measure ANOVAs) as well as on familiarity and liking ratings of the musical stimuli (independent-samples t-tests). Subsequent ANOVAs were performed to explore the moderating effect of BIS and BAS sensitivities on any significant effects obtained in the main analysis. Where required, Tukey's HSD and two-sided Dunnett's post hoc analyses were conducted to demarcate significant effects. An alpha level of .05 was set for all analyses.

1.2.2. Main data analysis

For the purpose of the main data analysis, the no music control group was used as a visual comparison, as this data-point was not completely crossed over music valence and interval variables. The control condition however, was included where relevant in post hoc analyses within single independent variables. Mean and standard error values for interval and music valence on LTM recognition scores are shown in Fig. 1A. Mean LTM recognition scores were substantially higher than the no music control when music was presented 20 min after learning the word list, regardless of music valence. In addition, positively valenced music appeared to yield an increase in recognition scores when presented immediately after learning.



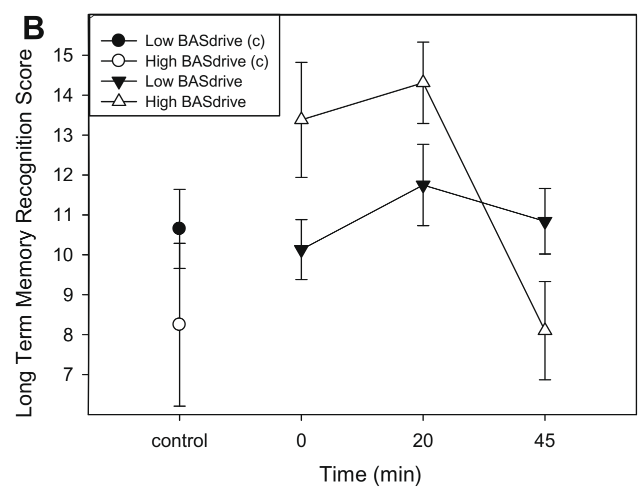


Fig. 1. Effects of music on mean LTM recognition scores as mediated by time of presentation after learning (immediately, 20 min and 45 min post-learning) and (A) music valence (positive and negative), or (B) BAS drive (low high) on mean LTM recognition scores. Error bars represent SEMs.

A two-way independent-measures ANOVA was conducted to explore the effects of interval and music valence on LTM recognition scores. The main effect for interval, $F(2, 120) = 4.98$, $p < .05$, η^2 partial = .08, with post hoc Tukey HSD tests revealed a significant difference between the 20 min interval ($M = 13.03$) and 45 min interval ($M = 10.00$) conditions, $p < .05$. Neither the interaction effect between interval and music valence, $F(2, 120) = 1.98$, $p > .05$, η^2 partial = .03, nor the music valence main effect, $F(1, 120) = 0.003$, $p > .05$, η^2 partial = .00, were significant.

Previous literature has suggested that differential responses to post-learning memory modulatory treatments may occur as a result of initial leaning ability (Torras-Garcia, Portell-Cortes, Costa-Miserachs, & Morgado-Bernal, 1997). Therefore, differences in free-recall scores (tested immediately after learning) across experimental conditions was examined. While free-recall scores were somewhat lower in the no music and Immediate/negative conditions, a two-way independent-measures ANOVA revealed no significant effects across music valence or arousal.

Participants' initial mood and arousal levels, as well as fatigue level were also evaluated as potential confounding variables (see Table 2). One-way between-group ANOVAs revealed no significant differences in initial mood, $F(6, 120) = 0.96$, $p > .05$, η^2 partial = .05, initial arousal, $F(6, 120) = 1.43$, $p > .05$, η^2 partial = .07, or fatigue levels, $F(6, 120) = 1.20$, $p > .05$, η^2 partial = .02.

Table 2
Means and standard deviations of initial mood, initial arousal and fatigue levels across groups.

	No music	0 min/positive	0 min/negative	20 min/positive	20 min/negative	45 min/positive	45 min/negative
Initial mood							
M	3.33	3.11	3.42	3.29	2.89	3.06	3.15
SD	.58	.88	.90	.73	.83	.77	.81
Initial arousal							
M	2.33	2.58	2.68	2.79	2.56	2.31	2.15
SD	.91	.84	.58	.97	.86	.79	.59
Fatigue							
M	3.00	2.79	3.16	3.00	2.33	2.69	2.75
SD	.77	.98	1.01	1.36	1.19	1.20	.91
$N = 127$							

1.2.3. Verification of music manipulations

To examine participants' perception of the musical stimuli heard, several single-sample *t*-tests were performed. Music arousal ratings differed significantly from the 'neutral' rating (indicated by '4') for the negative music piece only ($M = 4.56$, $SD = 1.12$), $t(56) = 3.81$, $p < .05$, two-tailed, $d = .50$ (positive music ratings: ($M = 4.07$, $SD = 1.74$), $t(48) = 0.30$, $p > .05$, two-tailed, $d = .04$). Music valence ratings differed significantly from the 'neutral' rating (also indicated by '4') for the positive music piece ($M = 5.67$, $SD = 1.00$), $t(48) = 11.72$, $p < .05$, two-tailed, $d = 1.67$; but not for the negative music piece ($M = 4.06$, $SD = 1.43$), $t(56) = 0.34$, $p > .05$, two-tailed, $d = .05$.

Both familiarity (Iwanaga, Ikeda, & Iwaki, 1996) and liking (Iwanaga & Moroki, 1999; Kreutz et al., 2008) have previously been found to moderate reactivity to music. Independent-samples *t*-tests however, revealed no significant difference in familiarity ratings for the positive ($M = 2.65$, $SD = 1.32$) and negative ($M = 2.79$, $SD = 1.28$) music pieces, $t(104)=-0.54$, $p >. 05$ (two-tailed), $d = .27$, nor any significant difference in liking ratings for either music piece (positive music ($M = 3.80$, $SD = .98$); negative music ($M = 3.49$, $SD = .91$), $t(104) = 1.66$, $p >. 05$ (two-tailed), $d = 0.71$).

1.2.4. Moderating effects of BIS/BAS sensitivities

The relationship between LTM recognition scores and dispositional BIS and BAS sensitivities (as measured by BIS, BAS drive, BAS fun-seeking and BAS reward-responsiveness scales) was initially investigated using Pearson product-moment correlations. No significant correlations were found between LTM scores and BIS, BAS fun-seeking, or BAS reward-responsiveness (all $p > .05$). However, a significant positive correlation was found between LTM scores and BAS drive, $r = .25$, $n = 127$, $p < .01$, indicating that 6.25% of the variation in LTM scores could be explained by higher levels of BAS drive sensitivity.

A median split was performed to categorize participants as low or high on BAS drive. Fig. 1B illustrates the mean and standard error values for low and high BAS drive sensitivities by interval on LTM scores.

As can be seen in Fig. 1B, mean LTM recognition scores were substantially higher when music was presented immediately or 20 min after learning the word list, when compared with the no music control and 45 min interval for high BAS drive sensitivity. There appears to be little difference however, in LTM memory scores for low BAS drive sensitivity across interval conditions relative to the control group.

A two-way independent-measures ANOVA was performed with the scores for positive and negative valence music pieces pooled (as no valence effects were observed in the main analysis). A significant interval by BAS drive interaction effect was observed, $F(3, 119) = 3.79$, $p < .05$, η^2 partial = .09. Simple main effects post hoc analyses revealed that the effect of interval on LTM recognition scores was significant only for participants with high BAS drive sensitivity scores, $F(3, 35) = 5.82$, $p < .05$, η^2 partial .33. A two-sided Dunnett's post hoc analysis revealed that the 20 min interval conditions differed significantly from the no music control group, $p < .05$.

To establish whether participant baseline BAS drive levels were comparable across experimental conditions, a one-way independent-measures ANOVA was performed. No statistically significant difference in BAS drive levels across conditions was revealed, $F(6, 120) = 0.92$, $p > .05$, η^2 partial = .04.

2. Discussion

The aim of the current study was to examine the time-dependent effects of positively and negatively emotionally arousing music on long-term word-list retention using a post-learning experimental paradigm. The moderating effect of BIS and BAS dispositional sensitivities formed a secondary level aim of the current investigation. The hypothesis that music of either valence (positive or negative) occurring up to 20 min, but not at 45 min following learning of a neutral word list would enhance long-term word-list retention was partially supported; the 20 min, but not immediate or 45 min interval conditions yielded enhanced LTM recognition scores regardless of music valence. Partial support was also provided for the hypothesis that the effect of music on long-term retention would be moderated by BIS/BAS sensitivity, with stronger effects observed for participants high on each of the BAS scales, and low on the BIS scale; participants high on BAS drive demonstrated enhanced recall when music was presented 20 min after learning, while music had no facilitatory effect on the memory of low BAS drive participants.

2.1. Time-dependent effects of music on long-term memory

The finding that music presented at 20 min, but not immediately or 45 min post-learning, significantly enhanced long-term word-list retention is, to our knowledge, the first demonstration that timing is critical to facilitation of memory by music. This observation is broadly consistent with previous human and animal model findings of time-dependent arousal facilitation effects on memory. For instance, Nielson and Powless (2007) found that emotional arousal induced any time up to 30 min, but not at 45 min post-learning significantly improved long-term retention for word list items. Similarly, Crowe et al. (1990) found an optimal 20 min post-training temporal window of memory susceptibility to stress hormone facilitation effects following subcutaneous administration of the arousal hormones noradrenaline, ACTH and vasopressin in neonate chicks. In contrast, administration at 30 min post-training or beyond was found to be ineffective (Crowe et al., 1990). In addition, Toukhsati and Rickard (2001) found that exposing young chicks to complex auditory stimuli enhanced memory when presented up to 30 min after weakly reinforced training, but not thereafter. Collectively, the current findings support the predominantly non-human literature that memory modulation is time-dependent (McGaugh, 2000), and more specifically, that facilitatory emotional arousal effects operate within narrow temporal parameters with an upper-most limit of around 25 min post-learning.

The absence of a facilitatory effect immediately post-learning, although unexpected in the context of the present study, has nonetheless been also reported in the animal literature. Gibbs and Summers (2002) found that subcutaneous introduction of propranolol prevented memory from 5 min before to 25 min post-training, with the exception of immediate and 20 min intervals. When administered intracranially however, inhibition of strongly reinforced memory differentially occurred between 5 and 25 min post-training. It is pertinent to consider that subcutaneous administration methods are less specific to the target region, and thus effects can be temporally less specific to the underlying mechanisms of memory modulation (Gibbs & Summers, 2002). In contrast, intracranial injections are more potent and direct, with temporal parameters more closely approximating the targeted mechanisms (Gibbs & Summers, 2002). In this context, it is possible that external administration of music mildly constrains the temporal specification of induced arousal. Furthermore, because a significant immediate interval effect was found by Nielson and Powless (2007), a possible advantage of a combined visual and auditory stimulus (i.e., film) is also plausible. Hence, for the music medium, it appears that arousal induced in close proximity, though not immediately after learning, might be optimal in enhancing long-term retention.

2.2. Valence and arousal effects

Negatively valenced sources of emotional arousal have almost exclusively been employed in previous studies (Cahill & McGaugh, 1995; Gibbs, 1991; Nielson et al., 2005). The present findings represent a much needed extension of the existing literature by showing that comparable memory enhancement can also be achieved using positively and negatively emotionally arousing stimuli. This also represents the first study to our knowledge to demonstrate this effect using music as the principal source of emotional arousal. As such, the results suggest that arousal, rather than valence, was responsible for the memory modulatory effects of the emotional music stimuli employed.

Central to the emotional arousal hypothesis, when an event is perceived as significant, there is concomitant release of adrenal stress hormones including epinephrine, norepinephrine and cortisol (Cahill & McGaugh, 1998; McGaugh, 2004; Zorawski & Killcross, 2003). Subjective music arousal ratings however, revealed that the two music excerpts were not subjectively perceived by participants as highly arousing. Replication of these data with physiological measures of arousal is therefore recommended to assess whether the stimuli did increase arousal levels, as it has previously been recognized that physiological arousal can increase in response to stimulating music in the absence of explicit increases in subjective ratings of arousal (e.g., Davis & Thaut, 1989; Rickard, 2004). Alternatively, the memory facilitation observed in this study may be explained by non-arousal based theories. For instance, there are commonalities in the processing of music and language in the brain (see Patel, 2008), such that activation by music may have a priming type effect on processing of a word list. However, it is not clear why music should facilitate memory when presented some 20 min after learning according to these explanations. In contrast, physiological arousal is known to act on consolidation processes of memory formation, and therefore is entirely consistent with this delayed effect. Taken together with the non-significant music valence effect, and the robust temporally defined effect of music presentation on LTM recognition scores, we conclude that, while indirect, the support for the emotional arousal proposition of neuromodulation is the most plausible.

A range of potential confounds were controlled in the current study, which strengthen the interpretation of these data. First, the word-list stimulus was extrinsic to the arousal source, and the arousal manipulation was introduced post-learning, so the effects can be quite confidently concluded to be on memory consolidation rather than attention or encoding processes. Secondly, subjective mood and arousal measures were highly consistent across experimental conditions prior to the music-arousal manipulation; fatigue levels were also comparable; and neither music piece was rated as more familiar or likable than the other. Therefore, differences in LTM recall is unlikely to be a confound of higher or lower baseline affect or arousal between groups; differential familiarity or liking of the music stimuli; nor one experimental procedure being more tiring than another. Finally, the initial learning ability of participants was consistent across experimental conditions, and therefore cannot account for differences in recall following the various music interventions.

2.3. Moderating effects of BIS and BAS sensitivities

The significant interaction between BAS drive and time of music presentation, with participants high on disposition BAS drive sensitivity yielding significantly higher memory recognition scores when music was presented 20 min after learning, provides additional insight into this effect. The BIS/BAS theory proposed by Gray (1991) contends that the BAS regulates appetitive motivation, and is sensitive to signals of potential reward and non-punishment, by activating approach behaviour, namely increasing arousal, and directing attention toward positive stimuli. Greater BAS sensitivity is also associated with a tendency to experience positive affect for appetitive cues. More specifically however, individuals who are high on the BAS subscale of drive have a tendency to strongly pursue appetitive goals. The differential result may therefore be attributable to an intrinsically higher receptivity to emotion-induction for individuals high on BAS drive sensitivity than for those low on BAS drive sensitivity. Further, the non-significant facilitation of music presented immediately after learning may therefore be partly accounted for by a substantial proportion of the sample being unresponsive to this emotional manipulation (that is, those who were low on the BAS-Drive scale), and thus diluting the strength of the effect. The non-significant finding for the 45 min interval remained consistent with the main analysis as well as prior research indicating that the efficacy of post-learning arousal treatments diminishes with time, such that they are most effective when administered soon after learning (McGaugh, 2000).

2.4. Future directions

The findings of the current study contribute to the emotion literature in several ways. Foremost, music appears to be a potent source of memory modulation. On the basis of similar memory enhancement effects for positively and negatively valenced film stimuli, the robust finding for time-dependence of arousal introduction was consistent with the arousal-based neuromodulation framework of memory consolidation. The data also suggest that high dispositional BAS drive sensitivity can moderate music reactivity. Finally, the obtained findings suggest that the valence of the arousal source is not a central feature in post-learning memory modulation processes, supporting recent reports in this regard (Nielson & Powless, 2007).

The current study was however, limited by a number of issues. For instance, false hits were not recorded in the LTM recognition test, which may have partially inflated recall scores, as a correction for guessing was not possible. Nonetheless, alternative procedures were employed to avoid a 'ceiling effect' for LTM recognition scores as participants were cautioned to select only those items that they were sure were from the original word list and that incorrect responses would be penalised. In addition, any such error should be distributed equally across the conditions and therefore are unlikely to account for the significant effects observed. In any case, future research could resolve this inherent ambiguity by computing the proportion of false hits, as well as administering a free recall test for word list items prior to the LTM recognition test to provide a more and accurate measure of LTM retention. In addition, in light on the robust 20 min interval effect on long-term word-list retention, it would also be informative for future research to further document smaller intervals (e.g., 5 min) between 0 and 20 min. Observing more specified intervals preceding 20 min has great potential to illuminate a minimum temporal interval post-learning where memory becomes sensitive to music-arousal enhancement.

In terms of practical implications, the findings of the present study offer important insights for music intervention strategies. In order to cultivate efficient therapeutic application, it is imperative that the conditions under which music might facilitate cognitive functioning are clearly defined, including the temporal parameters within which memory consolidation is susceptible to enhancement. Findings of the present study suggest that the 20 min post-learning interval is most effective (independent of the valence properties of the emotional arousal source). The specification of optimal temporal conditions supports Spintge and Droh's (1992) thesis that the efficacy of music-based treatments, like any other medical drug, depends on appropriate dosage (which includes duration and the time of administration). Importantly however, the efficacy of music on long-term retention also appears to be dependent on extra-musical factors, such as high dispositional BAS drive sensitivity of the listener. The 20 min temporal effect might form an effective supplement for the study habits of high BAS drive students, where flexibility over when to administer memory enhancing treatments is especially pertinent (i.e., test and examination times).

The selective facilitatory conditions of music illuminated in the current study (time of administration and high BAS drive sensitivity) offer valuable insights both for the existing emotion literature, and also the development of more specified memory intervention strategies in both clinical and educational arenas.

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