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A single bout of resistance exercise can enhance episodic memory performance

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ABSTRACT

Acute aerobic exercise can be beneficial to episodic memory. This benefit may occur because exercise produces a similar physiological response as physical stressors. When administered during consolidation, acute stress, both physical and psychological, consistently enhances episodic memory, particularly memory for emotional materials. Here we investigated whether a single bout of resistance exercise performed during consolidation can produce episodic memory benefits 48 h later. We used a one-leg knee extension/flexion task for the resistance exercise. To assess the physiological response to the exercise, we measured salivary alpha amylase (a biomarker of central norepinephrine), heart rate, and blood pressure. To test emotional episodic memory, we used a remember-know recognition memory paradigm with equal numbers of positive, negative, and neutral IAPS images as stimuli. The group that performed the exercise, the active group, had higher overall recognition accuracy than the group that did not exercise, the passive group. We found a robust effect of valence across groups, with better performance on emotional items as compared to neutral items and no difference between positive and negative items. This effect changed based on the physiological response to the exercise. Within the active group, participants with a high physiological response to the exercise were impaired for neutral items as compared to participants with a low physiological response to the exercise. Our results demonstrate that a single bout of resistance exercise performed during consolidation can enhance episodic memory and that the effect of valence on memory depends on the physiological response to the exercise.

1. Introduction

Studies examining the effects of exercise on cognition have focused on two types of exercise: aerobic and resistance exercises. Aerobic exercise refers to activities that involve large muscle groups and cause your body to increase its oxygen use. Examples of aerobic exercise include running, bicycling, and swimming. In contrast to aerobic exercise, resistance exercise does not increase oxygen use. Resistance exercise improves muscle tone, bone strength, balance, and coordination. Examples of resistance exercise include weightlifting, push-ups, and sit-ups. Both aerobic and resistance exercises are important for physical health, and both have been linked to cognitive benefits.

Long-term aerobic exercise interventions are associated with broad cognitive benefits (Dresler et al., 2013), including episodic memory (Kattenstroth, Kalisch, Holt, Tegenthoff, & Dinse, 2013). In addition, evidence suggests that resistance exercise training can improve episodic memory performance and executive functioning (Liu-Ambrose, Nagamatsu, Voss, Khan, & Handy, 2012; Voss, Nagamatsu, Liu-Ambrose, & Kramer, 2011). A variety of exercise regimens have been used to show these benefits, from traditional exercise to exergaming (Anderson-Hanley et al., 2012; Best, 2013) to dance (Coubard, Duretz, Lefebvre, Lapalus, & Ferrufino, 2011; Kattenstroth, Kalisch, Holt, Tegenthoff & Dinse, 2013). Overall, there is widespread agreement that various kinds of long-term exercise can improve cognitive function across the lifespan.

Single bouts of aerobic exercise after learning can also produce episodic memory improvements in young adults. For example, performance on recall tests (Labban & Etnier, 2011; Salas, Minakata, & Kelemen, 2011), face–name matching (Griffin et al., 2011), and paired associates learning (Nanda, Balde, & Manjunatha, 2013; Schmidt-Kassow et al., 2013; Winter et al., 2007) improve following a single bout of moderate aerobic exercise. Interestingly, high intensity exercise may impair subsequent recall (Eich & Metcalfe, 2009). These studies provide evidence that single bouts of moderate intensity aerobic exercise can be beneficial to episodic memory.

One reason why a single bout of exercise can yield cognitive benefits is that exercise is a physical stressor (Mastorakos, Pavlatou, Diamanti-Kandarakis, & Chrousos, 2005) and stressors have been shown to

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facilitate cognition under certain circumstances, as discussed below. Stressors result in the secretion of neuroendocrine mediators, which can be split into an initial rapid response from the sympathetic nervous system resulting in epinephrine and norepinephrine release and a slower response from the hypothalamic–pituitary–adrenal (HPA) axis resulting in cortisol release (for review, see Wolf, 2008). Increases in cortisol have been observed following both acute aerobic exercise (Fryer et al., 2012; Labsy et al., 2013; Usui et al., 2011; VanBruggen, Hackney, McMurray, & Ondrak, 2011; Wahl, Zinner, Achtzehn, Bloch, & Mester, 2010) and resistance exercise (Cadore et al., 2012; Hough, Papacosta, Wraith, & Gleeson, 2011; Leite et al., 2011; Pledge, Grosset, & Onambele-Pearson, 2011; Szivak et al., 2013; Uchida et al., 2009).

The beneficial effects of acute stress during consolidation on episodic memory have been demonstrated using both physical and psychological stressors. The cold pressor test (CPT) requires participants to hold one hand submerged in cold water for several minutes. Exposure to CPT immediately after learning can increase recall (Cahill, Gorski, & Le, 2003; Schwabe, Bohringer, Chatterjee, & Schachinger, 2008; Smeets, Otgaar, Candel & Wolf, 2008). A similar finding (Payne et al., 2006; Preuss & Wolf, 2009; Smeets, Giesbrecht, Jelicic, & Merckelbach, 2007) has been observed for the Trier Social Stress Test (TSST), a psychological stressor that requires participants to give a brief speech in the presence of others and perform a mental arithmetic task (Kirschbaum, Pirke, & Hellhammer, 1993). The benefits of these acute stressors emerge when the stress occurs during consolidation, defined as the period immediately following encoding (for review, see Wolf, 2008). Evidence suggests that the emotional valence of the to-be-remembered material changes the effect of stress on memory. There is evidence that stress selectively enhances emotional memory (Payne et al., 2007; Smeets, Otgaar, Candel, & Wolf, 2008) as well as evidence that stress selectively impairs neutral information (Payne et al., 2006).

The memory benefits resulting from stress induction are believed to be due to the effect of stress hormones (i.e., cortisol and epinephrine) on interactions between the amygdala and hippocampus; thereby enhancing consolidation of emotionally arousing materials (for review, see Roozendaal, McEwen, & Chattarji, 2009). Epinephrine, which is secreted from the adrenal medulla, induces the release of norepinephrine in the basolateral amygdala (BLA) by activating vagal afferents to the nucleus of the solitary tract (McGaugh & Roozendaal, 2002). In support of this idea, salivary measures of alpha amylase (AA), a marker of central norepinephrine, (van Stegeren, Rohleder, Everaerd, & Wolf, 2006) positively correlate with emotional memory performance. Cortisol also has been shown to positively correlate with the amount of emotional information remembered following CPT administration (Smeets et al., 2008). Exogenous administration of stress hormones also selectively enhances memory for emotional information (Segal & Cahill, 2009). Because a single bout of exercise produces the same kind of physiological responses, including increases in cortisol and norepinephrine, it is reasonable to predict that exercise during consolidation will improve memory for emotional materials.

Although it is possible that acute exercise during consolidation acts as a stressor, which facilitates memory in a similar manner to stressors like the TSST or CPT, it is also possible that episodic memory improvements following exercise may be the result of general arousal processes. Exercise produces physiological arousal via sympathetic nervous system activation. An arousing material tends to be better remembered than a non-arousing material, and this effect has been linked to amygdala activity (for review, see Talmi, 2013). The amygdala also plays a role in memory consolidation, particularly for emotional materials (McGaugh, McIntyre, & Power, 2002), and so increasing amygdala activity during consolidation through exercise could promote memory performance.

The present study investigated the effects of acute resistance exercise performed during consolidation on memory for emotional images. Resistance exercise (i.e. strength training) builds muscle mass and improves muscle tone. As a physical stressor, the body responds to resistance exercise in the same way as it responds to other stressors (Cadore et al., 2009; Kokalas, Tsalis, Tsigilis, & Mougios, 2004; Mastorakos, Pavlatou, Diamanti-Kandarakis & Chrousos, 2005). Thus, it is plausible that even a single bout of resistance exercise might enhance episodic memory accuracy via similar mechanisms as other acute stressors.

We predicted that AA, heart rate (HR), and blood pressure (BP) would increase following exercise in the active group and be related to memory accuracy. Furthermore, we predicted an interaction between emotional content and exercise, such that the active group would exhibit better memory for emotional items only. Extensive behavioral evidence indicates that memory for negative information depends on recollection to a greater extent than does memory for neutral and positive information (Comblain, D'Argembeau, Van der Linden, & Aldenhoff, 2004; D'Argembeau & Van der Linden, 2005; Dolcos, LaBar, & Cabeza, 2004; Kensinger & Corkin, 2003). Because of this, we wanted to examine the independent contributions of recollection and familiarity. To this end, we used a remember–know recognition test to assess memory performance (Yonelinas, Kroll, Dobbins, Lazzara, & Knight, 1998). Consequently, our final prediction was that recollection would be the highest for negative items, and greater in the active group compared to the passive group.

2. Method

2.1. Participants

Participants were randomly assigned to either the active or passive exercise conditions. There were 23 active participants (mean age = 20.61, 12 females) and 23 passive participants (mean age = 20.21, 17 females).[3] Active participants engaged in a resistance exercise task, and passive participants did not exercise. Participants received either $10 per hour and $5 per day for travel costs or course credit as compensation. Participants completed a health questionnaire to ensure that they did not have any medical conditions that could affect either their ability to complete the exercise task or the results of the study. Specifically, participants who had any of the following conditions were excluded from participating in this study: Parkinson's disease, Alzheimer's disease and other forms of dementia, multiple sclerosis, heart disease, untreated high/low blood pressure, a history of stoke or seizure, loss of consciousness, brain damage, heart attack, epilepsy, bipolar disorder, untreated depression or anxiety, Asperger's syndrome, attention deficit disorder, previous brain surgery, untreated cataracts, untreated glaucoma, macular degeneration, hearing difficulties, regular illegal drug use, obesity, left-handed individuals, sensory deficits in hands or legs, neurological disease, arthritis, cardiovascular disease, any fractures in the hand or leg within the past two years, or pregnant women. All participants signed consent forms approved by the Georgia Institute of Technology Institutional Review Board.

2.2. Materials

Stimuli for the episodic memory task consisted of 180 photographs from the International Affective Picture System (IAPS) and contained equal numbers of neutral, positive, and negative emotional images (Bradley & Lang, 2007). Appendix A contains a list of all of the IAPS images used for this study. The average valence and arousal ratings from the normed IAPS data are in Table 1. Negative images were more arousing that neutral [t (59) = 32.3, $p < 0.001$] and to a lesser extent positive images [t (59) = 2.34, $p = 0.02$]. Positive images were also more arousing than neutral images [t (59) = 29.9, $p < 0.001$]. The IAPS images consist of indoor and outdoor scenes containing people, objects, and animals. Negative images depict graphic and distressing

[3] We ran ANCOVAs with gender as a covariate, because of the gender differences in our groups. There were no main effects of gender or interactions with gender [all Fs < 1], so we concluded that gender was not a significant factor in our results.

Table 1
Normed valence and arousal ratings for IAPS images.

	Valence	Arousal
Neutral	5.25 (0.73)	2.71 (0.31)
Positive	7.05 (0.67)	4.92 (0.57)
Negative	3.17 (0.95)	5.16 (0.56)

Note: Standard deviations in parentheses.

scenes, for example mutilated bodies. Positive images included pleasant or uplifting scenes, such as children on a water slide. Neutral images do not evoke an emotional response, for example a wall clock.

Emotional state was assessed using the Positive and Negative Affect Schedule (PANAS) scale (Watson, Clark, & Tellegen, 1988). Participants completed the PANAS questionnaire at the beginning and end of both sessions. The PANAS is a 20-item questionnaire with 10 positive and 10 negative emotions or feelings. Participants are asked to indicate on a scale of 1 (very slightly or not at all) to 5 (extremely) the extent they feel this way at the present moment. BP and HR were recorded throughout both sessions using a vital monitor (Cardiocap/5, General Electric, Fairfield, CT). BP was assessed using systolic (Sys), diastolic (Dias), and mean arterial pressure (MAP). AA was measured 3 times during the first session: 45 min before exercise, halfway through exercise, and immediately after exercise. AA samples were acquired via salivette strips and analyzed using a salivary amylase activity monitor (Cocoro, Nipro Co., Osaka, Japan) (Yamaguchi et al., 2004). An isokinetic dynamometer (Humac Norm, CSMi Medical Solutions, Stoughton, MA) was used for the exercise portion of the study.

2.3. Procedure

There were 2 lab sessions, 48 h apart. Participants were instructed to refrain from caffeine, nicotine, and physical exercise for the 2 h prior to each session, and strenuous physical exercise between sessions. Fig. 1 shows the procedure for the experiment.

2.3.1. Session 1

The first session lasted between 1.5 and 2 h. First, participants performed a serial reaction-time (SRT) test. Immediately after the SRT, participants completed a practice encoding block of 12 trials to familiarize themselves with the episodic memory task. The encoding task contained 90 images and was split into 2 blocks of 45 images each to avoid fatigue. There were brief breaks (about 2 min) between blocks. There were 15 neutral images, 15 positive images, and 15 negative images in each block. Participants viewed one stimulus at a time in the center of the screen for 3000 ms, and a fixation cross was displayed in the center of the screen for 500 ms between stimuli. For each image, participants indicated whether the image could be found indoors and responded with 1 for yes and 2 for no on the keyboard. The question "Would you find this indoors?" and the response choices (1—yes, 2—no) were displayed with every stimulus. We used this encoding task to ensure that participants would be paying attention to the stimuli and to promote deep encoding of the material. Participants were not informed that they would be tested on these images.

The exercise portion of the study consisted of a knee extension/flexion task and was performed using an isokinetic dynamometer (Humac Norm, CSMi Medical Solutions, Stoughton, MA) immediately after memory encoding. Participants were seated in the dynamometer chair with their back erect, hips flexed to 85°, and knees flexed to 90°. In the active group, the protocol consisted of 1) warm-up with submaximal voluntary dynamic contractions, 2) maximal voluntary isometric contractions, and 3) maximal voluntary dynamic contractions. First, for the warm-up, participants performed 10 repetitions of submaximal knee extension and flexion in their maximal range of motion, gradually increasing their effort between the first and last repetitions. Second, to facilitate maximal voluntary activation in the next dynamic contractions, participants performed 5 repetitions of maximal voluntary isometric contractions with their leg held in 60° of extension. Each repetition consisted of 5-s maximal voluntary knee extension effort followed by 5-s maximal knee flexion effort. Third, for the maximal voluntary dynamic contractions, participants performed 6 sets of 10 repetitions of knee extension and flexion in their maximal range of motion with maximal effort. A 30-s rest was provided between sets and between isometric repetitions. A 5-min rest was provided between legs. The order of the leg was randomized across participants. In the passive group, participants remained relaxed and allowed the machine and the experimenter to passively move their leg between extension and flexion.

2.3.2. Session 2

The second session, conducted 48 h after the end of session 1, lasted approximately 1 h. For the procedural memory task, participants performed the same SRT task as the first session. Immediately after the SRT, participants completed a practice of the retrieval task with 24 trials. The retrieval task included the 90 studied images (30 neutral, 30 positive, and 30 negative) from the session 1 as well as 90 new images (30 neutral, 30 positive, and 30 negative). Retrieval was split into 4 blocks to avoid fatigue, with brief breaks (about 2 min) between blocks. Stimuli were displayed one at a time in the center of the screen for 6000 ms and a fixation cross was displayed for 500 ms between

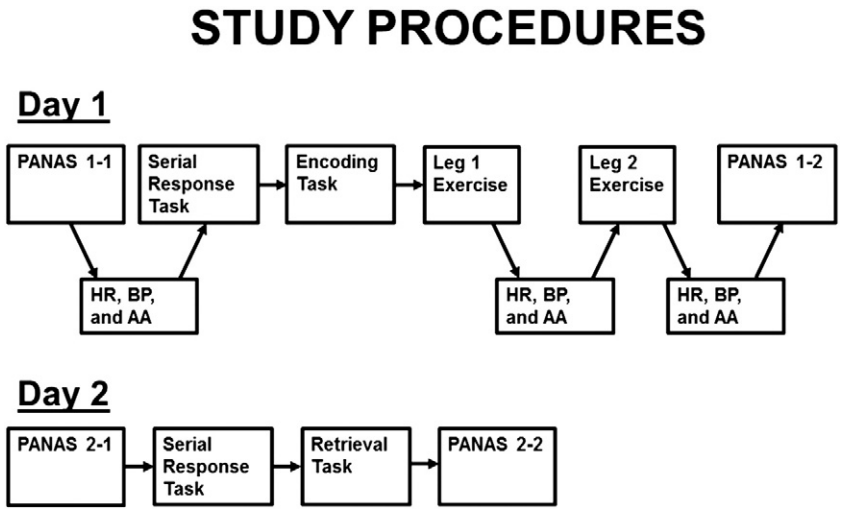

Fig. 1. Procedure. Flow chart of the procedure for both sessions. Note: HR = heart rate, BP = blood pressure, AA = alpha amylase.

Table 2
Physiological data.

			Before exercise	During exercise	After exercise
Active	AA		39.02 (32.43)	50.37 (43.51)	51.24 (44.15)
	HR		76.04 (11.30)	79.78 (8.73)	80.13 (9.92)
	BP	Systolic	118.83 (12.88)	119.09 (15.28)	120.35 (14.96)
		Diastolic	70.43 (7.92)	72.87 (8.26)	75.74 (10.489)
		Mean	87.00 (8.98)	88.52 (9.21)	92.39 (10.48)
Passive	AA		36.53 (25.69)	32.33 (25.16)	29.19 (15.38)
	HR		77.89 (8.28)	76.65 (8.51)	75.33 (8.38)
	BP	Systolic	115.44 (15.40)	111.78 (15.07)	113.17 (13.25)
		Diastolic	69.50 (8.29)	70.11 (8.41)	69.56 (8.30)
		Mean	81.56 (10.32)	80.83 (8.53)	82.67 (9.99)

Note: Standard deviations in parentheses. AA = alpha amylase, HR = heart rate, BP = blood pressure.

stimuli. Participants were instructed to respond "remember" if they were certain that they had seen the object and could recollect specific associations that occurred at study, "familiar" if they were certain about previously studying the object but could not recollect any specific associations, and "new" if they were certain they had never previously studied the object (Yonelinas, Kroll, Dobbins, Lazzara & Knight, 1998).

3. Results

For all statistical tests, the Huynh–Feldt correction was applied where appropriate and is reflected in the *p* values and the error terms.

3.1. Physiological data

Raw means across each group for the physiological measures are in Table 2. Physiological data were missing for 3 passive group participants due to technical difficulties and were replaced with the mean of the passive group.[4] Group differences were assessed with difference scores (score after exercise minus score before exercise). Fig. 2 displays the average change scores transformed into z-scores for the physiological measures for each group. The physiological data were submitted to a 2 (Time: before exercise, after exercise) × 2 (Group: passive, active) MANOVA with AA, HR, and BP[5] as dependent variables. There was a main effect of Time [*Pilai's Trace* = .815, $F(5, 40) = 35.215$, $p < .001$], a main effect of Group [$F(1, 44) = 4.697$, $p = .036$, $\eta^2 = .096$], and a Time × Group interaction [*Pilai's Trace* = .322, $F(5, 40) = 3.800$, $p = .007$]. The Time × Group interaction indicated that AA, HR, and BP were higher in the active group than in the passive group after the exercise. (See Table 3.)

To determine if the physiological measures changed significantly after exercise, the change scores for each group were compared to zero. In the active group, the changes in AA [$t(22) = 2.279$, $p = .033$], HR [$t(22) = 1.971$, $p = .061$], and BP [$t(22) = 3.932$, $p = .001$] were greater than zero. In the passive group, the change in HR was less than zero [$t(22) = 3.011$, $p = .006$], and the changes in AA [$t(22) = 1.429$, $p = .167$], and BP [$t(22) < 1$] were not different from zero.

3.2. Episodic memory data

Recognition memory was assessed using the P_r discrimination index; i.e. hit rate–false alarm rate (Snodgrass & Corwin, 1988). The P_r indices for each valence category and group can be seen in Fig. 3a. The data were submitted to a 2 (Group: passive, active) × 3 (Valence: neutral, positive, negative) ANOVA. There was a main effect of Group [$F(1, 44) = 5.430$, $p = .024$, $\eta^2 = .110$], indicating that the active group had higher accuracy than the passive group, as can be seen in Fig. 3a. There was a main effect of Valence [$F(1.798, 79.132) = 16.348$, $p < .001$, $\eta^2 = .271$], but no Valence × Group interaction [$F(1.798, 79.132) < 1$]. Follow-up t-tests indicated that participants remembered positive and negative stimuli better than neutral stimuli [$t(45) = 4.970$, $p < .001$] and [$t(45) = 4.377$, $p < .001$] respectively, with no difference between positive and negative stimuli [$t(45) = .429$, $p = .670$].

Estimates of recollection, calculated as remember hit rate–remember false alarm rate (Yonelinas, Kroll, Dobbins, Lazzara & Knight, 1998) are shown in Fig. 3b. The data were submitted to a 2 (Group: passive, active) × 3 (Valence: neutral, positive, negative) ANOVA. There was a main effect of Valence [$F(2, 88) = 15.331$, $p < .001$, $\eta^2 = .258$], which followed the same pattern as the effect for item memory. Participants recollected more positive and negative items than neutral items, [$t(45) = 4.840$, $p < .001$] and [$t(45) = 4.707$, $p < .001$] respectively, with no difference between positive and negative items [$t(45) = 1.118$, $p = .269$]. No other reliable effects were observed [$Fs < 1.806$, $ps > .186$].

To assess how the physiological response to exercise impacted recognition performance, data from the active group were submitted to a 2 (Response: high, low) × 3 (Valence: neutral, positive, negative) ANOVA. Response status was determined by averaging the z-score of each of the physiological measures and then dividing the group by a median split. Participants with scores above the median were classified as high responders, and participants with scores below the median were low responders.The physiological data for the high and low responders can be found in Table 3. There was a main

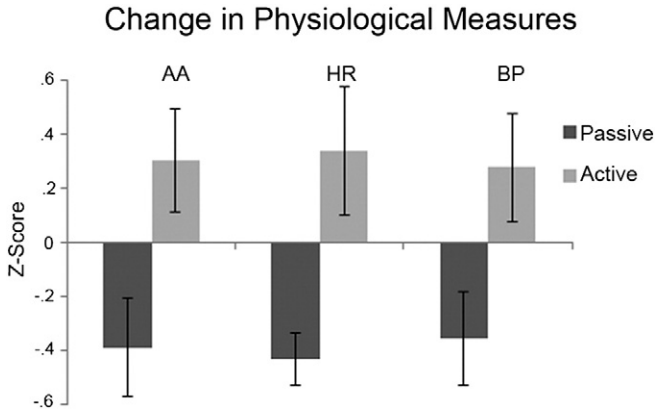

Fig. 2. Physiological data. Shows the change in the physiological measures after exercise converted into z-scores. Note: Data were converted to z-scores to show the change scores (after–before exercise) on a single scale. AA = alpha amylase, HR = heart rate, BP = blood pressure.

Table 3
Physiological data for high and low responders.

			Before exercise	During exercise	After exercise
High responders	AA		45.45 (31.55)	49.82 (48.50)	61.69 (54.32)
	HR		75.36 (12.38)	80.36 (9.58)	84.00 (10.88)
	BP	Systolic	117.64 (14.52)	121.55 (19.30)	125.91 (17.08)
		Diastolic	71.45 (8.44)	74.18 (7.86)	80.55 (7.20)
		Mean	86.82 (10.45)	89.45 (10.88)	97.45 (10.39)
Low responders	AA		33.13 (33.45)	50.88 (40.58)	41.75 (31.78)
	HR		76.67 (10.74)	79.25 (8.27)	76.58 (7.79)
	BP	Systolic	119.92 (11.71)	116.83 (10.80)	115.25 (11.09)
		Diastolic	69.50 (7.67)	71.67 (8.78)	71.33 (11.34)
		Mean	87.17 (7.87)	87.67 (7.77)	87.75 (8.52)

Note: Standard deviations in parentheses. AA = alpha amylase, HR = heart rate, BP = blood pressure.

[4] We conducted an additional analysis of the physiological data that omitted these 3 passive group participants. The results of this analysis do not differ from the results of the analysis that replaced these data with the mean of the passive group. There was a main effect of Time [*Pilai's Trace* = .804, $F(5, 37) = 30.301$, $p < .001$], a main effect of Group [$F(1, 41) = 4.072$, $p = .050$, $\eta^2 = .090$], and a Time × Group interaction [*Pilai's Trace* = .306, $F(5, 37) = 3.270$, $p = .015$].

[5] BP is the mean arterial pressure in these analyses. We also conducted analyses for systolic and diastolic pressures, and the results were not as robust.

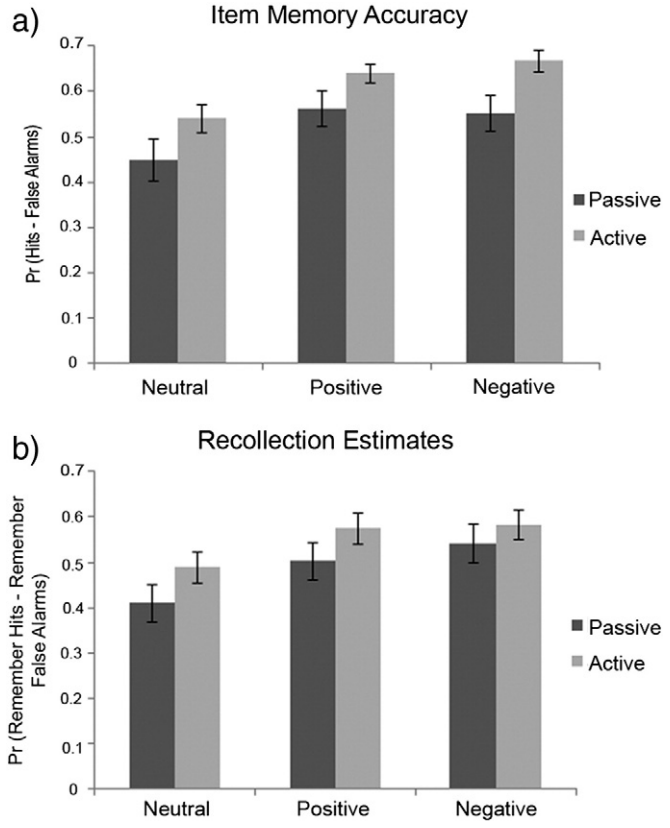

Fig. 3. Explicit memory data. a) Item Memory: Shows the Pr for each group for each valence category. b) Recollection estimates: Shows the remember Pr for each group for each category.

effect of Valence [$F(2, 42) = 10.987$, $p < .001$, $\eta^2 = .343$], no main effect of Response [$F(1, 21) < 1$], and a Response × Valence interaction [$F(2,42) = 3.950$, $p = .027$, $\eta^2 = .158$]. Importantly, the interaction reflects the fact that only the high responders show an effect of valence (high responders: [$F(2, 20) = 14.520$, $p < .001$, $\eta^2 = .592$]; low responders [$F(1, 21) < 1$]), as can be seen in Fig. 4. Follow-up ANOVAs were conducted for each valence category, and these results confirmed that low responders had higher recognition accuracy than high responders for neutral items [$F(1, 21) = 4.825$, $p = .039$, $\eta^2 = .187$], and high and low responders had similar accuracy for both positive [$F(1, 21) < 1$] and negative items [$F(1, 21) < 1$].

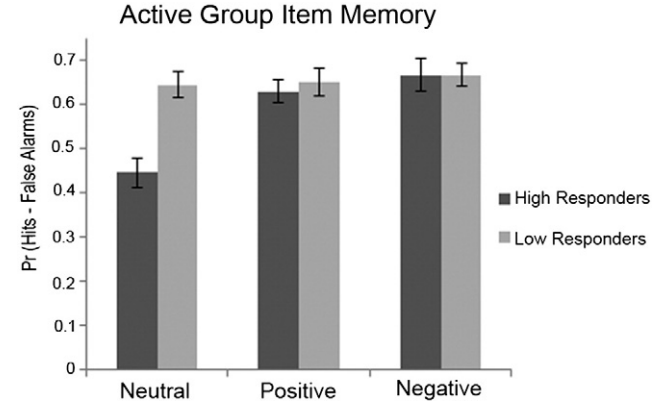

Fig. 4. Item memory accuracy for high and low responders in the active group. Shows the Pr for the high and low responders within the active group for each valence category.

4. Discussion

The results of this study indicate that a single bout of resistance exercise performed during consolidation can enhance episodic memory performance. This effect is consistent with studies of acute aerobic exercise that have also found memory improvements following exercise (Griffin et al., 2011; Labban & Etnier, 2011; Nanda, Balde & Manjunatha, 2013; Salas, Minakata & Kelemen, 2011; Schmidt-Kassow et al., 2013; Winter et al., 2007). Furthermore, we found that resistance exercise can produce physiological changes that follow the same pattern as physiological changes produced by acute stress. We found an average increase in AA of 12.22, which is consistent with an increase of 10.6 following the TSST found by Payne et al. (2007), but a smaller increase than that found by Smeets et al. (2008) of 30.98. Although HR and BP did increase following exercise, these increases were smaller in magnitude to those found previously in response to CPT (Coccoz, Maldonado, & Delorenzi, 2011; Schwabe & Wolf, 2010a, 2010b; Schwabe et al., 2008) and the TSST (Payne et al., 2007; Smeets et al., 2007). While the current study employed a one-leg knee extension/flexion task, it is possible that a more intense resistance exercise task (e.g., two-leg squat exercise with weight) would elicit greater increases in AA, HR, and BP. It would be interesting for future work to directly compare the physiological response to different types of acute stressors, as well as different intensities of acute bouts of exercise.

We predicted that exercise during consolidation would result in greater recognition accuracy particularly for recollection of negative items. While exercise during consolidation facilitated item recognition estimates across valence categories, with a similar albeit less robust pattern observed for recollection, memory was not particularly enhanced by exercise for emotional relative to neutral items. As predicted, both active and passive groups showed robust valence benefits in memory, recognizing positive and negative items better than neutral items, with no differences in accuracy between positive and negative items. There are a few possible explanations for the lack of interaction between valence and exercise and the lack of difference in memory between positive and negative items. First, we included positive and negative pictures that were roughly matched for arousal; with negative images only slightly more arousing than positive ones. The lack of difference between positive and negative memory estimates is therefore consistent with previous evidence suggesting that arousal, not valence, is the key factor determining why emotional items are often better remembered than neutral items (Dolcos et al., 2004; Dolcos et al., 2004; Dolcos et al., 2004, Kensinger et al. 2011, Kensinger & Schacter, 2005, Kensinger & Schacter, 2008). However, because the negative images were somewhat more arousing than the positive images as can be seen in Table 1, the effects of valence and arousal cannot be disentangled in the present study. Second, we used complex visual scenes as stimuli. Compared to words, pictures have been shown to engage emotional processing brain areas earlier (Giannotti et al., 2008; Schacht, 2008) and activate emotional responses more easily (Leclerc & Kensinger, 2011). Indeed, the high level of memory for emotional pictures is one reason why we included a 48 hour delay between study and test. It is possible that the high memory estimates across valence masked any more subtle effects of valence (i.e. positive vs. negative).

Importantly, although exercise during consolidation did not disproportionally improve emotional memory across the entire active group, we did find evidence for an interaction between physiological response and emotional memory in the active participants. Specifically, high responders in the active group were impaired for neutral items compared to low responders, while memory for the emotional items was the same for both high and low responders. This result is consistent with a previous finding that the TSST administered during consolidation selectively impaired neutral memory while leaving emotional memory intact (Payne et al., 2006). These results are consistent with the theory that acute stress during consolidation can be beneficial to memory for

emotional, but not neutral information. This may be because memory for neutral information is dependent on the hippocampus, while memory for emotional information relies on the amygdala. Increases in cortisol from stress facilitate activity in the amygdala (McGaugh, 2000), whereas high levels of cortisol disrupts hippocampal function (Kim & Diamond, 2002; Lupien & McEwen, 1997; Payne, Nadel, Britton, & Jacobs, 2004).

The neurological mechanisms underlying the beneficial effects of acute stress during consolidation on episodic memory are unknown, but rodent research points to a prominent role of both the amygdala and the hippocampus. Stress triggers the release of hormones like cortisol and epinephrine which facilitate noradrenergic activity in the basolateral nucleus of the amygdala (BLA) (McGaugh & Roozendaal, 2002). It is believed that this noradrenergic enhancement in the BLA is essential for consolidation. Indirect evidence for a similar mechanism in humans has been shown with administration of adrenergic antagonists, which inhibit central noradrenergic activity and reduce amygdala activity related to emotional memory processes (van Stegeren, Wolf, Everaerd, & Rombouts, 2008; van Stegeren et al., 2005; van Stegeren et al., 2007). Further work is needed to better determine whether the same mechanisms underlying stress-induced memory benefits in rodents exist in humans.

Although the results of this study appear to be consistent with studies finding episodic memory improvements following acute stress during consolidation, our effects may be driven by arousal rather than stress. A limitation of this study is that we did not measure the cortisol response to the resistance exercise. Cortisol is an important measure of HPA activity, and an increase in cortisol following exercise would bolster the argument that our resistance exercise task can be considered a physical stressor. We measured salivary AA, which increases following both stress and arousal. Therefore, it is possible that our observed increase in AA in the active group reflects increased arousal rather than stress. However, previous studies have found increases in cortisol following resistance exercise (Cadore et al., 2012; Hough, Papacosta, Wraith & Gleeson, 2011; Leite et al., 2011; Pledge, Grosset & Onambele-Pearson, 2011; Szivak et al., 2013; Uchida et al., 2009), so it is plausible that the resistance exercise task we used could also result in increased cortisol levels.

There are many potential therapeutic benefits of resistance exercise, both physical and cognitive, like the episodic memory benefit we have shown here. Unlike moderate long-term aerobic exercise, single bouts of resistance exercise are easy for a wide range of people with variable levels of physical ability to perform. We are not suggesting that single bouts of resistance exercise can replace the obvious health and cognitive benefits incurred from long-term aerobic interventions. Indeed, future research should examine the potential benefits of long-term resistance exercise interventions on the kinds of memory tasks used in the present study in order to determine the duration of these benefits and whether they may even delay cognitive decline in older adults and neurological patients.

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