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RESEARCH ARTICLE

Contributions of Arousal, Attention, Distinctiveness, and Semantic Relatedness to Enhanced Emotional Memory: An Event-Related Potential and Electrocardiogram Study

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Abstract
Enhanced emotional memory (EEM) describes memory benefits for emotional items, traditionally attributed to impacts of arousal at encoding; however, attention, semantic relatedness, and distinctiveness likely also contribute in various ways. The current study manipulated arousal, semantic relatedness, and distinctiveness while recording changes in event-related potentials and heart rate during memory encoding. Trials were classified as remembered or forgotten by immediate recall performance. Negative images were remembered significantly better than neutral, and related neutral images were remembered significantly better than unrelated neutral images. Higher P300 and late positive potential (LPP) amplitudes were associated with memory for negative images as compared with related neutral images, suggesting that negative images received additional attentional processing at encoding, and that this cannot be accounted for only by the inherent relatedness of negative stimuli. No encoding benefits were found for related neutral images though they were better remembered than unrelated neutral images, indicating retrieval dynamics impacted memory. When image types were intermixed, greater heart rate changes occurred, and negative and unrelated neutral images received increased elaborative processing as compared with related neutral images, perhaps due to the prioritization of encoding resources. These results suggest encoding and retrieval processes contribute to EEM, with emotional items benefiting additively.

Keywords EEG · EKG · Episodic memory · Emotion · Semantic relatedness · Distinctiveness

Experiencing an emotional event triggers a complex neuropsychological process that unfolds over time. The event engages arousal and alert systems (Reisberg & Heuer, 2004), and attention is prioritized towards some stimuli (Mather & Sutherland, 2011) which results in increased accuracy and vividness of memory (Kensinger, 2007). Though many theories have focused on arousal leading to enhanced attention at encoding, the reason for the enhancement of emotional memory (EEM) is likely more complicated (Talmi, Lohnas, & Daw, 2017). To investigate this, participants often study and later recall negative and neutral images. Negative images are frequently processed as distinctive, recruiting different processing relative to neutral images in temporal or spatial proximity. In addition, negative images are also inherently thematically related (e.g., death, attack), which may differentially engage cognitive processes at encoding and serve as an organizing factor aiding retrieval. The current study sought to understand mechanisms of EEM by examining factors at both encoding and retrieval in one study.

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Arousal at Encoding

Highly arousing stimuli trigger an immediate orienting response modulated by noradrenergic inputs to the locus coeruleus along with an autonomic response leading to immediate engagement of the amygdala (Sara & Bouret, 2012; Sommer, Gläscher, Moritz, & Büchel, 2008). Due to limited attentional resources, arousal may help guide attention based on salience and goal relevance (Mather & Sutherland, 2011). Whenever stimuli appear at a predictable rate, heart rate decreases in anticipation of an important event, and increases at stimulus onset (Jennings & Hall, 1980). These changes in heart rate can reflect an arousal response (Bradley & Lang, 2007), which may be linked to an increase in attention or cognitive effort (Jennings & Hall, 1980), and subsequently increased memory (Bradley, Greenwald, Petry, & Lang, 1992; Buchanan, Etzel, Adolphs, & Tranel, 2006). Despite the theoretical importance of arousal's allocation of attention, few studies have examined how arousal interacts with attention at encoding or the stimulus factors which alter processing at encoding and retrieval.

Attention at Encoding

Attention is prioritized towards emotional stimuli (e.g., Anderson & Phelps, 2001; McKenna & Sharma, 1995). However, attention alone does not predict EEM (Mickley Steinmetz & Kensinger, 2013; Riggs, McQuiggan, Farb, Anderson, & Ryan, 2011; Talmi, Luk, McGarry, & Moscovitch, 2007a), particularly in immediate recall when consolidation has not yet impacted memory (Talmi, Schimmack, Paterson, & Moscovitch, 2007b).

Behavioral measures provide only discrete snapshots of attentional deployment; however, event-related potential (ERP) analyses can be used to examine early and late attentional processes. The P300 waveform (250–500 ms post-stimulus) is associated with motivated attention and contextual updating, and can be enhanced by emotion (Barnacle, Tsivilis, Schaefer, & Talmi, 2018; Donchin & Coles, 1988; Olofsson & Polich, 2007; Thomas, Johnstone, & Gonsalvez, 2007). Additionally, the late positive potential (LPP; 400–1000 ms post-stimulus) is an index of elaborative processing (Todd, Lewis, Meusel, & Zelazo, 2008; Yao et al., 2016). Emotion may increase the LPP due to enhanced emotion regulation or self-referential processing (Watts, Buratto, Brotherhood, Barnacle, & Schaefer, 2014). These waveforms can give insight into what encoding processes predict memory by averaging trials which are subsequently remembered or forgotten and examining differences between these two trial types (Dm effect).

Semantic Relatedness at Encoding and Retrieval

Emotional stimuli are often semantically related, while neutral stimuli are unrelated in most experiments (Buchanan et al., 2006; Doerksen & Shimamura, 2001; Talmi & Moscovitch, 2004). For example, participants may more easily group emotional pictures thematically like a homeless man, a burning car, and a hospitalized man, than neutral pictures such as a truck, a cup, and a chess player. At encoding, semantic organization guided by activity in the prefrontal cortex can enhance encoding efficiency via chunking-related items (see Blumenfeld & Ranganath, 2007). At retrieval, an internally generated cue such as a schema can aid recall (Phelps et al., 1998). The emotional Context Maintenance and Retrieval (eCMR) model supports considering both encoding and retrieval, suggesting that retrieval must be considered to fully account for memory processes (Talmi et al., 2017).

Distinctiveness at Encoding

Another factor potentially influencing EEM is the primary distinctiveness, or local context, of the stimuli (Schmidt, 1991; Talmi & McGarry, 2012). We define distinctiveness as an independent variable, a psychological representation that differs either in evoked arousal or conceptually from the processing of other items held in working memory (Hunt, 2006; Schmidt, 1991). Emotional items presented in mixed lists with neutral items may benefit from selective attention and deficient processing of neutral stimuli (Watts et al., 2014). Watts and colleagues (2014) found reduced memory-related activity (Dm effect) for neutral stimuli in mixed lists compared with those in pure lists, which present only categorically homogenous images. However, Barnacle et al. (2018) more carefully controlled for semantic relatedness of neutral stimuli and found no differences in ERP activity associated with motivated attention for neutral information across list types. This may indicate that considering the interactions between these factors is required to fully explain the behavioral findings of context-dependent EEM.

Given the possible interactive effects among these factors, emotion, relatedness (negative related, related neutral, and unrelated neutral images), and distinctiveness (mixed and pure lists) were manipulated while investigating measures of attention (P300, LPP) and arousal (heart rate), followed by immediate recall tests.

First, we investigated encoding to see if relatedness or distinctiveness alone modulated arousal and attention, or if the two factors interact. We hypothesized that interactions would occur, as Watts et al. (2014) found a distinctiveness effect (differences between mixed and pure lists) when not controlling for relatedness, while Barnacle et al. (2018) did not find a distinctiveness effect when controlling for relatedness (see Table 1C). However, no previous study has examined ERP and heart rate effects while manipulating both distinctiveness and relatedness in the same study, so it is possible that main effects may occur instead of an interaction (see Table 1A&B). Secondly, we investigated the relationship between encoding and retrieval to see if arousal and attention at encoding predict

Table 1 Theoretical logic behind each pattern of results

A. Logic regarding distinctiveness (main effect)				
Can enhanced arousal and attention at encoding be accounted for by distinctiveness?	Predictions if…	Arousal/attention (P3, LPP, HR)	Explanation	
	Yes	Neutral mixed lists < neutral pure lists	Based on the theory that in mixed lists negative information may steal processing capacity from the neutral images (Watts et al., 2014), if there are lower levels of arousal and attention (deficient processing) for neutral images only in mixed lists, then distinctiveness modulates arousal and attention at encoding.	
	No	Neutral mixed lists = neutral pure lists	Distinctiveness does not modulate arousal and attention at encoding.	
B. Logic regarding relatedness (main effect)				
Can enhanced arousal and attention at encoding be accounted for by relatedness?	Predictions if…	Arousal/attention (P3, LPP, HR)		Explanation
	Yes	Negative images = neutral related images	Negative images > neutral unrelated images	If the comparison neutral images evoke equal arousal and attention levels only when they are also equally related, then we know that this boost in encoding activity can be accounted for by relatedness.
	No	Negative images > neutral related images		If neutral images are matched on relatedness to negative images, but negative images still evoke increased arousal and attention, then we know that this boost in encoding activity cannot be accounted for by relatedness alone.
C. Logic regarding the function of relatedness at encoding and retrieval				
Does arousal and attention at encoding match subsequent memory at retrieval?	Predictions if…		Conclusion	
	Yes	Pattern of results at encoding will directly predict memory.	Encoding accounts for the effect of relatedness on memory.	
	No	Pattern of results at encoding will not directly predict memory.	Encoding does not account for the effect of relatedness on memory.	

Participants viewed lists that included a series of images. For each, they were asked to immediately recall what images they remembered. In order to manipulate relatedness, participants were shown images that were negative, neutral related (equally related to the negative images), and neutral unrelated (less related than other image types). To manipulate distinctiveness, some participants were presented with mixed lists which included all of these images mixed together in each study list, while others were presented with pure lists which contained lists that included only negative images, only neutral related images, and only neutral unrelated images. For A–C, the dependent variable is arousal as measured by changes in heart rate and attention as measured by changes in the early ERP component P300 (250–500 ms post-stimulus) and the late ERP component, the late positive potential (LPP; 400–1000 ms post-stimulus). For the ERP components, encoding activity was investigated by examining the Dm effect: comparing encoding activity for trials that were later remembered as opposed to later forgotten. In this way, it is possible to examine what happens specifically in ERP waveforms during encoding which might predict which images are later remembered

A) In order to determine if there is a main effect of relatedness on arousal and attention at encoding, the relevant comparison here is between negative stimuli and neutral images that were matched on relatedness. If relatedness alone explains EEM, then one would expect that encoding-related attention and arousal would not differ when negative stimuli are equal in relatedness to neutral stimuli

B) In order to determine if there is a main effect of distinctiveness on arousal and attention at encoding, the relevant comparison here is between mixed and pure lists for neutral stimuli. This is because past studies have suggested that, in mixed lists, negative stimuli may steal processing capacity from neutral stimuli. This would be indicated in the current study by diminished encoding-related attention and arousal for neutral stimuli in mixed lists as compared with pure lists. This would not occur in pure lists where there is no competition for resources. Behavioral studies have sometimes found that neutral stimuli are less likely to be remembered in mixed lists, as compared with pure lists (Barnacle, Montaldi, Talmi, & Sommer, 2016; Dewhurst & Parry, 2000; Schmidt & Saari, 2007; Talmi, Luk, et al., 2007a; Talmi & Moscovitch, 2004). However, it is not always the case that distinctiveness alone fully accounts for EEM (Kamp, Potts, & Donchin, 2015; Schmidt & Saari, 2007; Talmi & McGarry, 2012; Talmi & Moscovitch, 2004; Talmi, Schimmack, et al., 2007b)

C) One way that relatedness and distinctiveness may interact based on past literature is that for neutral unrelated stimuli, encoding-related attention and arousal for mixed and pure lists may differ (Watts et al., 2014), while for related stimuli, they may not (Barnacle et al., 2018). This would suggest that any deficient processing for neutral stimuli in mixed lists would only happen when stimuli are related. However, if relatedness functions more at retrieval than at encoding, this may be reflected in the memory results, but not in the arousal and encoding-related attention-based waveforms

D) Comparing arousal and attention at encoding to memory results allows us to determine if encoding can fully predict what is later remembered. If increased arousal and attention at encoding matches later memory, this is evidence that these factors at encoding predict later memory. However, if encoding does not predict memory, that indicates that factors at retrieval play a role. Since relatedness functions both at encoding and retrieval, relatedness may be able to account for any potential memory differences in this case the pattern of results for subsequent memory retrieval. Because of the function of relatedness at retrieval and the eCMR model (Talmi et al., 2017), we predicted that encoding activity would not directly predict which item types are remembered best (see Table 1D).

Method

Participants

Eighty-four undergraduate students (58 female) between the ages of 18 and 22 (*M* = 19.98, SE = 0.125) participated in this study for course credit or a $20 Amazon gift card. All participants provided written informed consent and procedures were approved by the Wofford College Institutional Review Board. Six participants were excluded from analysis on the basis of prior exposure to the images (*n* = 2), left-handedness (*n* = 1), connection failure (*n* = 1), and a neurological disorder (*n* = 2). This resulted in a sample of 79 participants (54 female) included in the memory analyses. All participants were right-handed, did not have any neurological disorders, had not received general anesthesia in the 2 weeks prior to testing, and did not sustain a concussion in the month prior to testing. All participants were randomly assigned to pure (*n* = 39, 24 female) and mixed (*n* = 40, 30 female) list conditions.

For the ERP analysis of subsequent memory due to either artifacts or superior or inferior memory levels, participants may have a low number of trials in a particular condition, rendering the results for that condition to be ambiguous and prone to error. To combat this, as in past studies (e.g., Barnacle et al., 2018), participants were required to have at least 12 trials in each of the six memory bins. Twenty participants were excluded from ERP analysis for having fewer than 12 trials in any of the six memory bins described below. This resulted in a sample of 59 participants (33 female) included in the ERP analyses, 28 (19 female) in the pure, and 31 (24 female) in the mixed list conditions.

Materials

Sixty-six negative, 66 related neutral, and 66 unrelated neutral images were methodically selected to fit into the three categories of images: negative, related neutral, and unrelated neutral images (see Fig. 1 for example stimuli). Images were taken from the International Affective Picture System (Lang, Bradley, & Cuthbert, 1999), the Geneva Affective Picture Database (Dan-Glauser & Scherer, 2011), the Emotional

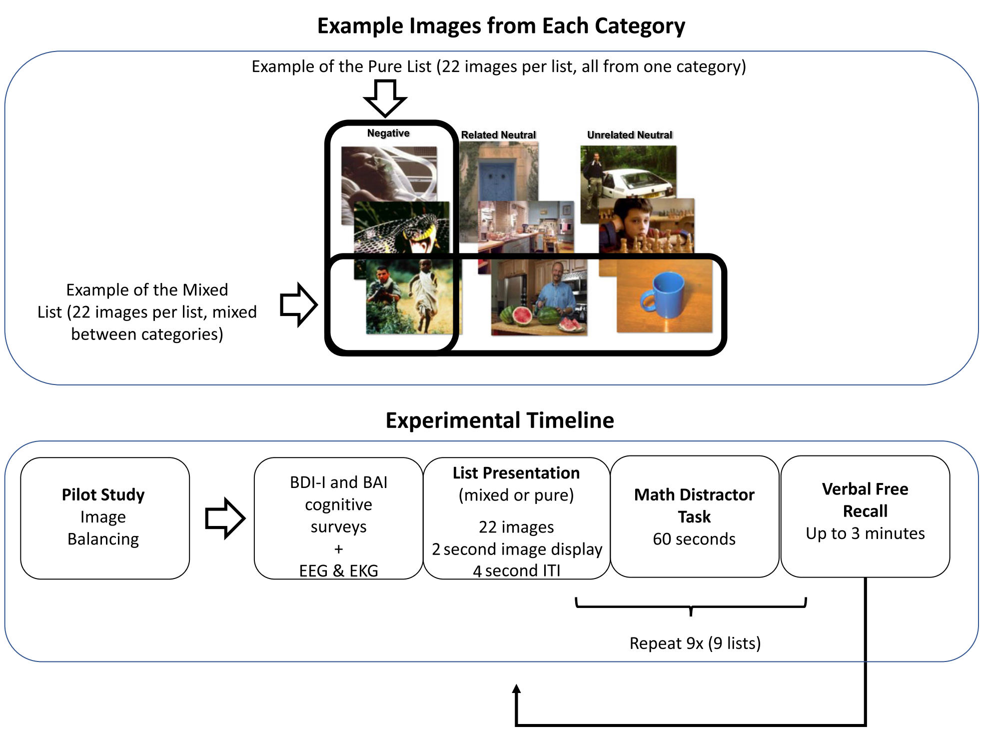

Fig. 1 Study timeline and image examples for negative, related neutral, and unrelated neutral image types. The top part of the graph shows example images from each category (negative, related neutral, unrelated neutral). The thick black boxes depict an example of sample images from the pure lists (in which images were from the same category) and sample images from the mixed lists (in which images were mixed between the different categories). The bottom part of the figure represents the experimental timeline. Images were normed via a pilot study. When participants came into the laboratory, they first completed cognitive and affective surveys. EEG and EKG recordings were taken while they viewed 9 lists. Each list had 22 images, each shown for 2 s with a 4-s inter-trial interval. At the end of each list, participants completed a math distractor and then were asked to freely recall all the pictures that they remembered.

Picture Set (Wessa et al., 2010), the image pool of Talmi et al. (2007), and Google Images. All images were resized to 500 by 400 pixels. The luminosity rating was also calculated for each image using Photoshop, and three independent raters rated each image for its complexity on a 7-point Likert scale. Two pilot studies were conducted to obtain ratings for each image on valence, arousal, and relatedness so that the images could be matched within and across lists on these factors.

Valence and Arousal Ratings In the first pilot study, valence and arousal ratings were obtained from a pool of 100 unrelated neutral images, 150 related neutral images, and 150 negative images. Twelve ratings were obtained for each image. Valence was rated on a 9-point Likert scale anchored by "very unpleasing" and "very pleasing." Arousal was also rated on a 9-point Likert scale anchored by "calm/soothing" or "exciting/agitating."

Relatedness Ratings In order to obtain images that were grouped according to a particular theme in the case of negative and related neutral images, we adopted the protocol of Barnacle et al. (2018), who used only these two types of stimuli. As we also included unrelated neutral images, we additionally ensured that unrelated stimuli were indeed rated low in relatedness. Participants were shown pairs of images and were asked to rate how related these images were on a 7-point Likert scale from "low association" to "high association." In order to help define high and low association, participants were given examples of categorically related images (a handgun and a rifle; walking and running) as well as thematically related images (an umbrella and clouds; Talmi, Luk, et al., 2007a).

To-be-rated images from the related neutral category were selected such that they could conceivably fall under a certain theme. For example, a neutral image that had a cupboard and one that had a dinner table were identified under the representative theme of domesticity.

In order to reduce the total number of ratings that were obtained if every image was paired with every other image, and to group images according to themes, the images from the pool were visually inspected to come up with nine plausible themes for each category of images. An image was selected from each of these themes to serve as a template image. Thus, all images within the negative image pool were matched to each of the nine negative template images in order to obtain a score of relatedness. Each image pairing received 12 independent ratings. Similarly, images anticipated to be related neutral images were paired with each of the nine related neutral template images in order to be rated on relatedness. All images in the unrelated neutral image pool were matched to every other image within the pool of unrelated neutral images in order to confirm that they were not related (except for 12 of the 7650 combinations which were excluded due to a programming error).

List Construction

Balancing Using these ratings, particular images were selected so that all lists were balanced: Negative and neutral images differed significantly on valence and arousal, but not on luminosity or complexity (see Table 2). Similarly, negative and related neutral images were balanced such that they did not differ on relatedness, though both were significantly more related than unrelated neutral images. To further ensure that these ratings did not differ between each of the nine lists, a four-factor nested ANOVA was also conducted (see Supplemental Materials) and confirmed that this pattern of ratings did not differ across each list.

Distinctiveness: Mixed and Pure Lists The images were also divided into pure lists and mixed lists. In pure lists, only one type of image was included in each list (e.g., all negative images, all related neutral images, or all unrelated neutral images), and in

Table 2 Overall image balancing ratings for negative, related neutral, and unrelated neutral image types based on arousal, valence, relatedness, luminosity, and complexity. Pilot participants scored images based on arousal (9-point scale), valence (9-point scale), relatedness (7-point scale), and complexity (7-point scale). Image balancing comparisons show no significant differences in luminosity or complexity between image types

Overall image balancing across image types

	Negative		Related neutral		Unrelated neutral	
	Mean	SE	Mean	SE	Mean	SE
Arousal	7.212	0.075	4.872	0.083	4.838	0.068
Valence	2.711	0.074	5.139	0.086	5.090	0.058
Relatedness	3.626	0.085	3.589	0.048	1.981	0.017
Luminosity	106.105	3.048	106.353	1.304	107.516	3.030
Complexity	3.025	0.085	3.062	0.116	3.025	0.134

Image balancing comparisons between selected image pools

	Unrelated neutral to related neutral	Negative to unrelated neutral	Negative to related neutral
Arousal	.752	< .001	< .001
Valence	.634	< .001	< .001
Relatedness	< .001	< .001	.706
Luminosity	.724	.743	.940
Complexity	.838	.999	.801

mixed lists, all three types were included. The purpose of this was to manipulate distinctiveness, or local context of the stimuli. Here we define distinctiveness as an independent variable, a psychological representation that differs from the processing of other items held in memory, or its local context (Hunt, 2006). By defining distinctiveness in this way, the change in processing can be evoked by a number of factors such as if the stimulus evokes a differing emotional response from surrounding stimuli, or if it is incongruent, varying conceptually or visually (Schmidt, 1991). Mirroring past studies (e.g., Barnacle et al., 2018; Talmi, Schimmack, et al., 2007b; Watts et al., 2014), we sought to manipulate distinctiveness by comparing lists including images from the negative, related neutral, and unrelated neutral stimuli intermixed (mixed lists) and lists occurring with only one image type (pure lists). In this way, mixed lists included items that were distinctive in two ways: (1) in that they evoked a differing emotional response, as in the case of negative as compared with neutral images (both related and unrelated), and (2) in that they did not all belong to a particular theme. As relatedness was manipulated, negative stimuli differed conceptually from related neutral stimuli. Unrelated neutral stimuli did not vary along a theme, so each stimulus was likely to have been processed as conceptually distinct from previous stimuli.

Recall Lists To create the series of immediate recall tests, images were carefully divided into nine mixed lists and nine pure lists, such that the aforementioned balancing of valence, arousal, relatedness, luminosity, and complexity differences remained within each list and did not differ between lists. Each list included 22 images, and the same images were used when creating the mixed and pure lists. For pure lists, there were three lists for each image type (negative, related neutral, and unrelated neutral). For the mixed list group, all three image types were mixed together in each list. Thus, for mixed lists, there were seven or eight images of each type per list. An additional related neutral list and an additional mixed list were created to be used as the practice list from unselected images rated in the initial pool. See Supplemental Materials Table 3 for the descriptions of images included in each list.

Materials also included a 19-item version of the Beck Depression Inventory (BDI-I; Beck, Ward, Mendelson, Mock, & Erbaugh, 1961) and a 21-item Beck Anxiety Inventory (BAI; Beck, Epstein, Brown, & Steer, 1988). These measures were included to provide information about participants' levels of anxiety and depression, as both have been implicated in differences in how the brain processes emotional, and especially negative, stimuli. Images were presented in E-Prime 3.0 (Psychology Software Tools, Pittsburgh, PA).

Procedure

After informed consent, a 32-channel Active Two electrode cap (Behavioral Brain Sciences Center, Birmingham, UK) was applied while participants completed the BDI-I, BAI, and the practice test. The practice test consisted of one full list consisting of 22 images.

For each list, images were presented for 2-s of passive viewing followed by a 4-s inter-trial interval (ITI) (Talmi & McGarry, 2012) intended to reduce emotional carryover effects. Though brain activity was recorded during the entire task, each event-related potential analysis commenced when each image appeared on the screen. Immediately following image presentation of the 22 images, participants completed a 60-s task of arithmetic to reduce rehearsal. The free recall period began at the end of the 60-s delay period and lasted up to 3-min, although the period was terminated early if the participants indicated they were finished. Participants were instructed to recall images only from the list that they had just studied and to provide enough detail that the image could be identified from the list. An experimenter recorded the participant's verbal recall responses and asked the participant for additional detail on ambiguous answers. This cycle of images, distractor, and recall was repeated for each of the nine lists. Participants had an opportunity for a self-timed break after each list's recall period. See Fig. 1 for the procedure schematic.

Images within each list were presented in a random order. In the mixed list condition, the order of list presentation was also randomized. In the pure list condition, lists were presented in pseudorandom order with each list type presented before repeating a list type. This was done in order to prevent practice or fatigue effects differentially impacting one category. The first two images of each list were not included in analyses to control for the primacy effect. In both the pure and mixed list conditions, image order was randomized within each of the nine lists presented to each participant, meaning the two buffer images were always randomized, as well. For the pure lists, images of the same type (negative, unrelated neutral, related neutral) were always excluded, as there was only one image type in each list. To ensure these buffer images were distributed evenly across the image type in the mixed list condition, we ran a one-way ANOVA comparing the final number of image trials used in analysis for each image type and found no significant difference of number of image trials among the three image types ($F < .8$, $p > .4$).

Data Processing and Reduction

Images were coded as remembered or forgotten by two independent raters who matched participant descriptions to images from the list and classified them as remembered, forgotten, or unclear. Images were classified as remembered if the image could be identified within the list and discriminated from other images in the list. Inter-rater reliability was high: 99.18%.

Offline physiological analyses were performed using the EMSE Software Suite (Source Signal Imaging, San Diego, CA, USA). All sites were referenced to two mastoid electrodes. Electrode offsets were between 0 and ± 30 mV.

Signals were amplified, bandpass filtered (0.03–30 Hz), and digitized at 1024 Hz. Two EOG electrodes were used to track eye movements. Three EKG electrodes also recorded heart rate data during the experiment. Some participants wore a Holter monitoring device to record heart rate for 24- h following completion of the EEG session. The 24-h data are not presented in the current manuscript. Trials were binned to create ERP waveforms by image type and subsequent memory status, which resulted in the six following bins: (1) forgotten unrelated neutral, (2) remembered unrelated neutral, (3) forgotten related neutral, (4) remembered related neutral, (5) forgotten negative, and (6) remembered negative. Data were epoched for 100 ms before image onset until 1500 ms after image onset. Blinks were removed using the EMSE manual artifact tool and were removed from 6.48% of remembered unrelated neutral trials, 9.00% of forgotten unrelated neutral trials, 9.44% of remembered related neutral trials, 9.59% of forgotten related neutral trials, 12.38% of remembered negative trials, and 10.51% of forgotten negative trials.

Following precedents set in ERP research for affective picture processing, in order to study the P300 waveform, for each participant, the maximum value between 300 and 400 ms post-stimulus was calculated for electrode Fz and then averaged across each category (Olofsson, Nordin, Sequeira, & Polich, 2008). Being a discrete waveform, the P300 is typically measured according to the maximum amplitude of its peak or the relative difference between the peak and the preceding trough of the N2 waveform. For the current study, the 300–400 ms post-stimulus latency window contained the trend of the entire P300 waveform, without including the subsequent positive potential. To study the late positive potential (LPP), for each participant, the average value between 400 and 1000 ms post-stimulus was calculated for electrodes Pz, CP1, and CP2 and then averaged across each category (Weinberg & Hajcak, 2010). An average is taken instead of a maximum amplitude to examine the LPP because it is a positive trend of electrical activity, as opposed to a discrete waveform. Differences were found between mixed and pure lists for the LPP using electrodes Fz and Pz (see Supplemental Materials) but were not found when we looked at the posterior central group that included Pz, CP1, and CP2 that is often used to examine the LPP for neutral stimuli (Weinberg & Hajcak, 2010). Since past studies have shown that LPP may be enhanced in the anterior left hemisphere in response to negative stimuli (Cunningham, Espinet, DeYoung, & Zelazo, 2005), we wondered if the presence of CP2 in the right hemisphere grouping may have washed out any emotion effects that we may have seen in the central electrodes. Thus, we also included a left anterior electrode group to examine this possibility including electrodes F7, F3, and FC5. Average values between 400 and 1000 ms post-stimulus were used in order to capture the differences in the extent that the LPP was sustained over time.

The participants' EKG data, recorded during each of the 9 segments, was split into 6-s intervals in order to (a) account for voltage drift and (b) extract interval data for each individual image. Each 6-s interval was initiated the moment the participant began to view a given image and ended the moment before the following image was shown. These segments were normalized with a range of − 1 to 1 with respect to voltage and filtered through MATLAB's Savikzky-Golay filter. MATLAB's "findpeaks" algorithm was then used to identify each R-wave peak in order to extract RR-interval data. Each 9-segment EKG data string was then hand cleaned by noting the times at which the program misidentified an R-wave, and noting the times where the program failed to identify an R-wave. The original R-wave strings generated by the program were then corrected to include the missing R-waves and remove the misidentified R-waves using these hand-recorded times. The result of this process was a clean string of RR-interval data for each image the participant viewed. Heart rate was then calculated for two periods per image: One period was for 3-s after the stimulus first appeared on the screen and the second period was for the 3-s before each image first appeared on the screen (during the fixation cross). In order to look at the heart rate change for each image, the difference in heart rate between these two periods was calculated for each image, subtracting the heart rate after an image occurred from before an image occurred.

Results

Behavioral Results

To determine if there was an effect of the type of image on participants' recall for the mixed and pure conditions, two image type (negative, related neutral, unrelated neutral) × list type (pure, mixed) ANCOVAs were conducted on recall memory (number of pictures remembered out of total possible in each category). One ANCOVA included anxiety (BAI) as a covariate, while the other included depression (BDI). As the purpose of including these covariates was simply to control for these factors, any main effects or interactions with BAI and BDI for this and all following analyses are reported in the Supplemental Materials. Accounting for both anxiety and depression respectively, a significant main effect of image type was found, $F(2,\ 152) = 72.733$, $p < .001$, $\eta_p^2 = .489$; $F(2,\ 152) = 87.615$, $p < .001$, $\eta_p^2 = .535$. Post hoc *t*-tests revealed significantly better memory for negative images ($M = 0.543$, SE = 0.014) as compared with unrelated neutral images ($M = 0.370$, SE = 0.015; $t(78) = 15.047$, $p < .001$) and related neutral images ($M = 0.461$, SE = 0.016; $t(78) = 6.309$, $p < .001$). Additionally, related neutral images were remembered significantly better than unrelated neutral Images, $t(78) = 8.813$, $p < .001$ (see Fig. 2). There was no significant interaction of list type and image type. This suggests a main effect of relatedness, and no interaction between relatedness and distinctiveness.

Our experiment was substantially longer than previous studies. Most past behavioral studies that included the same conditions as the current study included approximately 50–100 fewer images (e.g., Talmi, Luk, et al., 2007a). ERP studies necessitate more trials to allow for remembered vs. forgotten Dm analyses. Thus, in order to compare with previous behavioral studies, we also examined differences in list order by grouping the lists into three categories: early (lists 1–3), middle (lists 4–6), and late (lists 7–9). Two 3 × 2 × 3 ANCOVAs were conducted on recall memory including image type (negative, unrelated neutral, related neutral) by list type (pure, mixed) by list order (early, middle, later). One ANCOVA included anxiety (BAI) as a covariate, while the other included depression (BDI). Accounting for both anxiety and depression respectively, these analyses revealed a significant main effect of list order ($F(2, 152) = 10.993$, $p < .001$, $\eta_p^2 = .126$; $F(2, 152) = 3.852$, $p = .023$, $\eta_p^2 = .048$), a significant main effect of image type ($F(2, 152) = 72.495$, $p < .001$, $\eta_p^2 = .488$; $F(2, 152) = 87.950$, $p < .001$, $\eta_p^2 = .536$), and a list order × image type interaction, $F(4, 304) = 2.911$, $p = .022$, $\eta_p^2 = .037$; $F(4, 304) = 4.433$, $p = .002$, $\eta_p^2 = .055$. These effects were qualified by a significant three-way interaction between image type, list type, and list order, $F(4, 304) = 3.865$, $p = .004$, $\eta_p^2 = .048$; $F(4, 304) = 3.931$, $p = .004$, $\eta_p^2 = .049$ (see Table 2). In addition, a main effect of BAI and a BAI × list order interaction were also found (see Supplemental Materials).

Post hoc paired sample t-tests were conducted to further explore the 3-way interaction. Similar to past studies, a difference in recall memory between pure and mixed lists occurred (Dewhurst & Parry, 2000; Schmidt & Saari, 2007; Talmi, Schimmack, et al., 2007b). However, this only occurred in the first grouping of experimental lists (early: lists 1–3). For these early lists, participants remembered unrelated neutral images significantly better in the pure list condition ($M = 0.465$, $SE = 0.029$) than in the mixed list condition ($M = 0.373$, $SE = 0.025$), $t(77) = 2.394$, $p = .019$. No other significant differences were found for other image types between pure and mixed lists or within middle or later test lists. This suggests an interaction between relatedness and distinctiveness, but only in the first lists.

In addition, looking at a comparison between list orders instead of directly between mixed and pure lists provided a look at how changes differed as the experiment went on. Order effects emerged only for unrelated neutral images in the pure list condition. For participants in the pure list condition, memory for unrelated neutral images declined as the experiment went on. Unrelated neutral images were remembered significantly more in early lists ($M = 0.465$, $SE = 0.029$) than in middle lists ($M = 0.323$, $SE = 0.024$), $t(38) = 4.985$, $p < .001$, and in early lists than in late lists ($M = 0.350$, $SE = 0.023$), $t(38) = 5.012$, $p < .001$. For other image types in the pure list condition, and for participants in the mixed list condition, no significant differences were found for any image type between early, middle, and late lists.

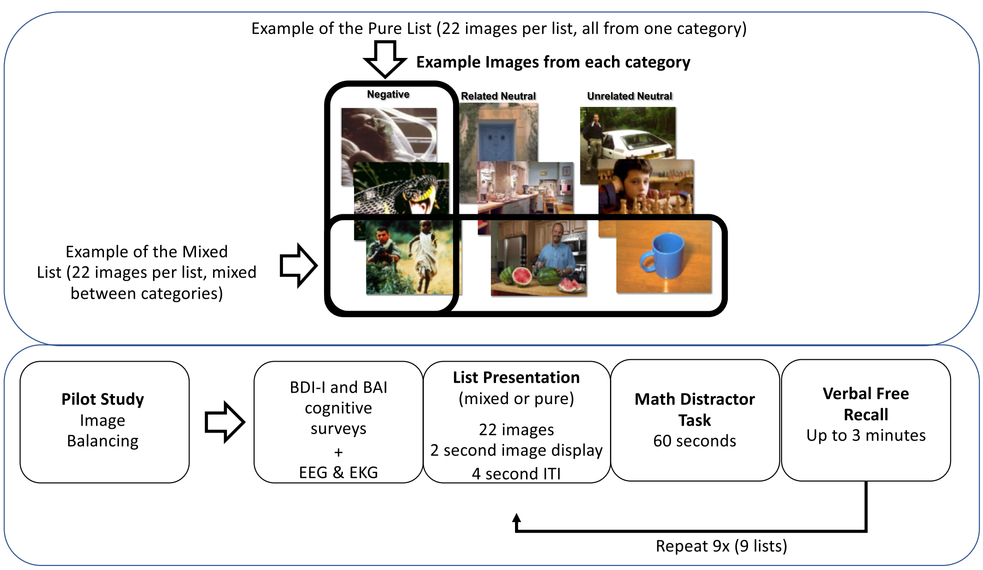

Fig. 2 Mean percentage of remembered images for negative, unrelated neutral, and related neutral images in both pure and mixed lists. Memory was significantly better for negative items as compared with related neutral images which was better than memory for unrelated neutral images, but did not significantly differ based on pure or mixed lists. Error bars indicate standard errors of the mean. Asterisks denote significant difference at $p < .05$

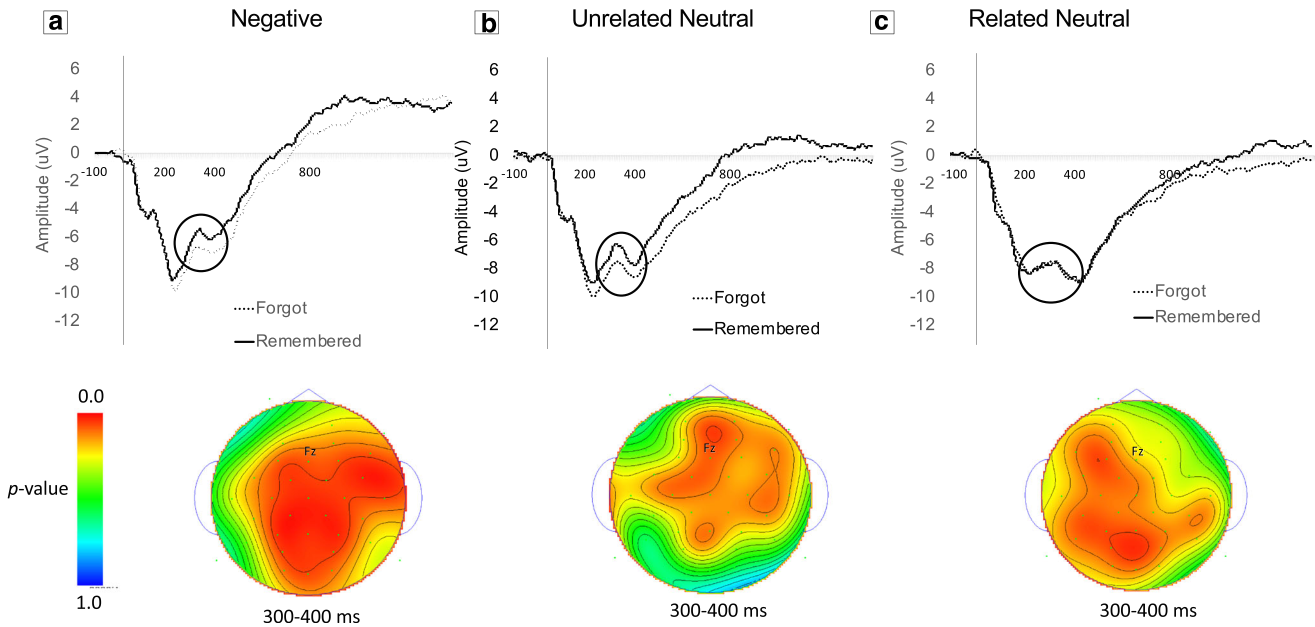

Fig. 3 Subsequent memory (Dm) for each image type from the Fz electrode. **a** Negative. **b** Unrelated neutral. **c** Related neutral images. The black circle indicates the P300 (300–400 ms). A significant Dm effect was found for the P300 for negative and unrelated neutral images, but not related neutral images. The two-dimension scalp maps below each graph plot the uncorrected *p*-value for remembered minus forgotten for the P300

ERP Results

Waveform Analyses: P300

In order to inspect differences in the P300 waveform, the maximum voltage between 300 and 400 ms post-stimulus was calculated at electrode Fz for each participant and category was submitted to two ANCOVAs: image type (negative, unrelated neutral, related neutral) × memory (remember, forgot) × list (mixed, pure). One ANCOVA included anxiety (BAI) as a covariate, while the other included depression (BDI). Accounting for both anxiety and depression respectively, these analyses revealed a main effect of memory ($F(1, 54) = 21.757$, $p < .001$, $\eta_p^2 = .287$; $F(1, 54) = 16.698$, $p < .001$, $\eta_p^2 = .236$) as well as an interaction between image type and memory, $F(2, 108) = 3.442$, $p = .036$, $\eta_p^2 = .060$; $F(2, 108) = 4.079$, $p = .020$, $\eta_p^2 = .070$. See Fig. 3. This interaction was such that there was no significant Dm effect for related neutral images (no significant difference between remembered and forgotten images), $p < .3$. However, there was a significant Dm effect for negative and unrelated neutral images. Negative images that were later remembered ($M = -4.285$, SE = 0.694) had a greater amplitude than those later forgotten ($M = -5.441$, SE = 0.717), $t(58) = 2.308$, $p = .025$. Similarly, neutral unrelated images that were later remembered ($M = -4.201$, SE = 0.785) had a greater amplitude than those later forgotten ($M = -6.547$, SE = 0.717), $t(56) = 4.416$, $p = .001$.

Waveform Analyses: LPP

In order to inspect differences in the LPP waveform, the average value between 400 and 1000 ms post-stimulus was calculated at the electrode group including Pz, CP1, and CP2 (Weinberg & Hajcak, 2010) for each participant and category and submitted to two ANCOVAs: image type (negative, unrelated neutral, related neutral) × memory (remember, forgot) × list (mixed, pure). One ANCOVA included anxiety (BAI) as a covariate, while the other included depression (BDI). Accounting for both anxiety and depression respectively, these analyses revealed a significant main effect of image type ($F(2, 106) = 16.914$, $p < .001$, $\eta_p^2 = .242$; $F(2, 106) = 22.100$, $p < .001$, $\eta_p^2 = .294$) as well as a main effect of memory ($F(1, 53) = 15.572$, $p < .001$, $\eta_p^2 = .227$; $F(1, 53) = 12.309$, $p = .001$, $\eta_p^2 = .188$) qualified by an image type × memory interaction, $F(2, 106) = 4.996$, $p = .008$, $\eta_p^2 = .086$; $F(2, 106) = 3.727$, $p = .027$, $\eta_p^2 = .066$. Just as for the P300, the interaction was such that negative images exhibited a Dm effect: Those that were later remembered ($M = 1.108$, SE = 0.712) had a significantly larger LPP than those later forgotten ($M = -0.670$, SE = 0.654), $t(58) = 3.401$, $p = .001$. Similarly, unrelated neutral images exhibited a Dm effect: Those that were later remembered ($M = -0.285$, SE = 0.717) had a larger significantly LPP than those later forgotten ($M = -2.500$, SE = 0.592), $t(56) = 4.649$, $p < .001$, while there was no Dm effect for related

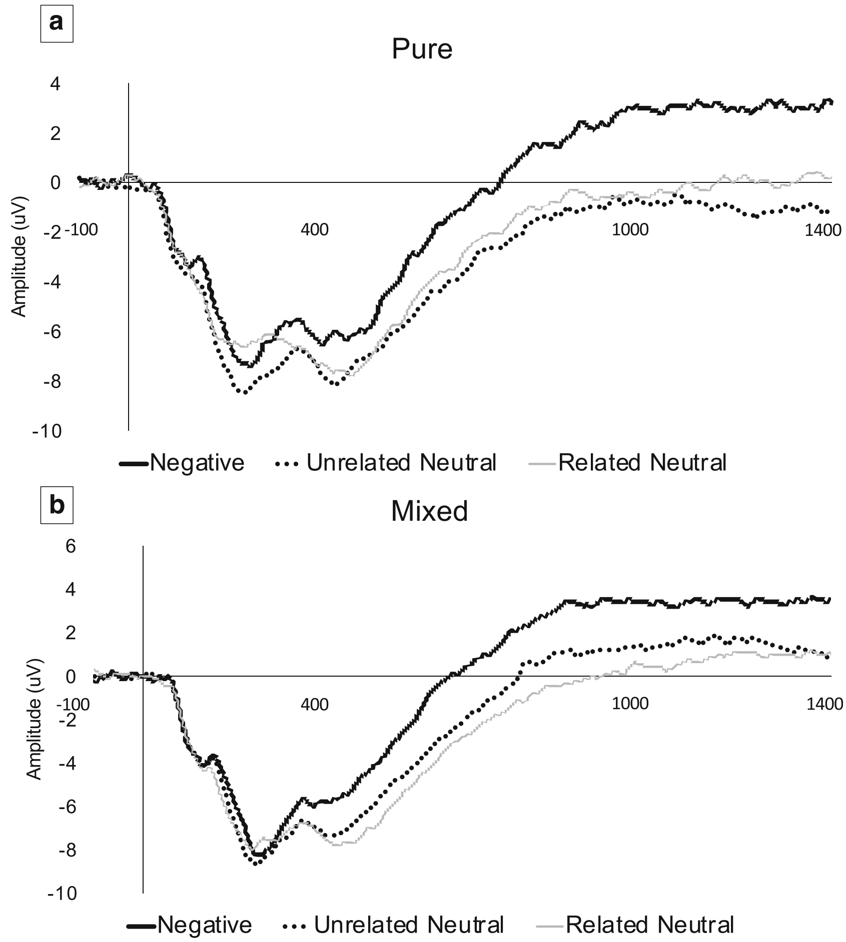

Fig. 4 Differences in neuropsychological processing based on item type (negative, unrelated neutral, and related neutral images) for the left anterior electrodes (F7, F3, and FC5). **a** Pure. **b** Mixed lists. While for pure lists, the negative images had a higher amplitude than all neutral images, and for mixed lists, negative images had a higher LPP (400–1000 ms post-stimulus) than unrelated neutral which had a higher amplitude than related neutral images

neutral images (i.e., no difference in the LPP between remembered and forgotten related neutral images), $p > .50$.

In order to investigate changes in the LPP for the left hemisphere, due to the use of negative stimuli (Cunningham et al., 2005), we also investigated the LPP waveform, using the electrode group including F7, F3, and FC5. Again, the average value between 400 and 1000 ms post-stimulus was calculated for each participant and image type and these data were used in two ANCOVAs: image type (negative, unrelated neutral, related neutral) × memory (remember, forgot) × list (mixed, pure). One ANCOVA included anxiety (BAI) as a covariate, while the other included depression (BDI). Accounting for both anxiety and depression respectively, these analyses revealed significant main effects of image type ($F(2, 108) = 14.361$, $p < .001$, $\eta_p^2 = .210$; $F(2, 108) = 14.110$, $p < .001$, $\eta_p^2 = .207$) and of memory ($F(1, 54) = 18.208$, $p < .001$, $\eta_p^2 = .252$; $F(1, 54) = 8.811$, $p = .004$, $\eta_p^2 = .140$) in addition to an interaction of list type × image type, $F(2, 108) = 3.460$, $p = .035$, $\eta_p^2 = .060$; $F(2, 108) = 3.310$, $p = .040$, $\eta_p^2 = .058$. See Fig. 4.

The list type × image type interaction was such that for the pure lists there was the highest average LPP for negative images ($M = -1.124$, SE = 0.793) which was significantly higher than related neutral images ($M = -2.856$, SE = 0.802; $t(27) = 3.332$, $p = .003$) and unrelated neutral images ($M = -3.765$, SE = 0.823; $t(27) = 4.711$, $p < .001$). However, there was no significant difference between unrelated and related neutral images, $t(27) = 1.748$, $p = .092$. For the mixed lists, negative images ($M = 0.512$, SE = 0.696) had a significantly greater LPP than related neutral images ($M = -2.602$, SE = 0.632; $t(30) = 6.061$, $p < .001$) and unrelated neutral images ($M = -1.743$, SE = 0.617; $t(30) = 4.330$, $p < .001$). In addition, unrelated neutral images had a greater LPP than related neutral images, $t(30) = 2.476$, $p = .019$. Thus, there was an interaction between distinctiveness and relatedness such that there was a distinction in neutral images based on relatedness for the pure list, but not the mixed list.

In addition, a memory × anxiety (BAI) interaction was also found (see Supplemental Materials).

Heart Rate Analyses

First, it was important to establish that there were not overall arousal differences in heart rate baseline between mixed and pure lists. In order to investigate this, the baseline 3-s before each image was averaged across each image type for each participant

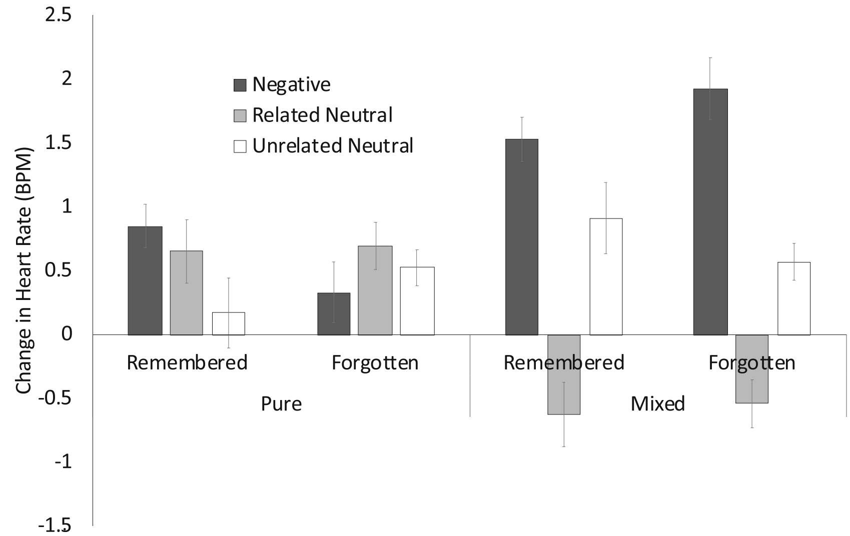

Fig. 5 Change in heart rate (bpm) for both pure and mixed lists separated by remembered and forgotten negative, related neutral, and unrelated neutral images. Change in heart rate was measured by subtracting the average recorded heart rate 3-s post-image from the recording 3-s before the image. This means that a positive number would indicate that the heart rate decreased from baseline, and a negative number would indicate that the heart rate increased from baseline. Error bars indicate standard errors of the mean. For pure lists, there was a greater change in heart rate for remembered items for negative images as compared with unrelated neutral images. For mixed lists, both remembered and forgotten images, each category of images significantly differed from each other with the largest heart rate change for negative images, and a significantly smaller heart rate change for unrelated neutral images. For related neutral images, change in heart rate was lower than that of negative and unrelated neutral images

and compared between mixed and pure lists. This analysis revealed no significant difference in baseline heart rate between mixed and pure lists for any image type, all $p > .470$.

Given this, it was then possible to investigate changes in heart rate across image and list types. Heart rate change was calculated as the average heart rate during the image presentation subtracted from the preceding 3-s baseline. This means that a positive number would indicate that the heart rate decreased from baseline, and a negative number would indicate that the heart rate increased from baseline. Two image type (negative, unrelated neutral, related neutral) × memory (remembered, forgotten) × list (mixed, pure) ANCOVAs were conducted on change in heart rate (beats per minute, difference from baseline, the fixation cross before each picture). One ANCOVA included anxiety (BAI) as a covariate, while the other included depression (BDI). See Fig. 5. Accounting for both anxiety and depression respectively, these analyses revealed a main effect of image type ($F(2, 112) = 16.824$, $p < .001$, $\eta_p^2 = .231$; $F(2, 112) = 30.573$, $p < .001$, $\eta_p^2 = .353$) qualified by an image type × list type ($F(2, 112) = 61.942$, $p < .001$, $\eta_p^2 = .525$; $F(2, 112) = 58.745$, $p < .001$, $\eta_p^2 = .512$) and a memory × image type × list type interaction, $F(2, 112) = 4.126$, $p = .019$, $\eta_p^2 = .069$; $F(2, 112) = 3.537$, $p = .032$, $\eta_p^2 = .059$. This three-way interaction was such that for pure lists there were very few differences in heart rate change between image categories. The only significant difference was that there was a greater change in heart rate for remembered items for negative images ($M = 0.851$, SE = 0.190), as compared with unrelated neutral images ($M = 0.169$, SE = 0.272), $t(29) = 2.437$, $p = .021$. However, for mixed lists for both remembered and forgotten images, each category of images significantly differed from each other with the largest heart rate change for negative images (remember: $M = 1.544$, SE = 0.132; forgot: $M = 1.915$, SE = 0.175), and a significantly smaller heart rate change for unrelated neutral images (remembered: $M = 0.903$, SE = 0.266; forgotten: $M = 0.564$, SE = 0.120) (remembered: $t(31) = 6.529$, $p < .001$; forgotten: $t(31) = 6.529$, $p < .001$). For related neutral images (remember: $M = -0.616$, SE = 0.130; forgot: $M = -0.611$, SE = 0.148), there was a significantly lower change than that for negative images (remembered: $t(34) = 12.035$, $p < .001$; forgotten: $t(34) = 12.472$, $p < .001$) or unrelated neutral images (remembered: $t(31) = 5.734$, $p < .001$; forgotten: $t(31) = 5.745$, $p < .001$). Thus, heart rate also showed an interaction between distinctiveness and relatedness.

Discussion

The current study investigated attention and arousal alongside semantic relatedness and distinctiveness to understand how these factors contribute to EEM. Negative images were associated with P300 and LPP Dm effects as well as better memory. Neutral images matched on relatedness to negative images evoked smaller P300 and LPP Dm effects than negative images, suggesting relatedness alone cannot account for the changes in encoding that facilitate EEM. In addition, the P300 and LPP Dm effects did not predict the increased memory recall of related compared with unrelated neutral images, which supports the idea that relatedness aids memory due to functions existing beyond encoding. Lastly, distinctiveness alone did not impact changes in arousal and attention. Instead, distinctiveness interacted with relatedness in three instances: memory results for early lists,the LPP waveform regardless of later memory, and heart rate.

Relatedness

Relatedness alone could not account for enhanced arousal and attention at encoding. Despite neutral images being matched on relatedness with negative images, negative images evoked both a larger P300 Dm and LPP Dm effect (Table 1, "No"). This suggests negative images engage more attention and working memory (Donchin & Coles, 1988; Talmi & McGarry, 2012) as well as elaborative processing (Cuthbert et al., 2000) beyond what can be accounted for by relatedness.

The Function of Relatedness at Encoding and Retrieval

Though a larger Dm effect was associated with better memory for negative stimuli, the Dm effect failed to predict later memory for some neutral stimuli (Table 1, "No"). Although related neutral images were better remembered than unrelated neutral images, there was no P300 or LPP Dm effect for related neutral stimuli. This suggests encoding alone does not account for the effect of relatedness on memory for neutral images. The eCMR model suggests that mismatches between attention and memory (Barnacle et al., 2018) can be explained by the combination of factors at both encoding and retrieval (Talmi et al., 2017). At retrieval, the immediate context of the most recently recalled items may have facilitated subsequent recall of additional related neutral images (Polyn, Norman, & Kahana, 2009; Talmi et al., 2017). Similarly, unrelated neutral stimuli may be less likely to be remembered than related neutral stimuli due to being more difficult to retrieve. A future study could investigate this hypothesis by manipulating conditions at retrieval.

Interaction between Relatedness and Distinctiveness

Memory

For the first group of lists, unrelated neutral images were recalled more often in pure lists than in mixed lists (Table 1, "Yes"), which is consistent with previous results indicating deficient processing for neutral stimuli when mixed with emotional stimuli (Talmi & McGarry, 2012; Talmi & Moscovitch, 2004). The effect was not maintained after the first group of lists, which could be because the current study included more images than used in previous studies (Talmi, Luk, et al., 2007a), because all image types were viewed before a list type was repeated, or because participants developed strategies to overcome the deficit in memory for unrelated neutral stimuli in mixed lists.

LPP

The LPP waveform showed an interaction between relatedness and distinctiveness when examining the left anterior electrodes. This effect did not interact with memory, suggesting that while relatedness influenced LPP and later memory (Dm), the influence on sustained processing occurred regardless of if the images were later remembered. In both mixed and pure lists, there was a greater LPP for negative as compared with neutral images, mirroring the results of Barnacle et al. (2018). However, in mixed lists, there was a larger LPP for unrelated neutral images than related neutral images, and in pure lists, there was not a significant difference between unrelated and related neutral images. This may suggest that when lists are mixed, a prioritization of how sustained attentional resources are allocated may occur. Unlike most other studies, this study included both related and unrelated neutral images in mixed lists, which may have influenced which items received sustained attention. Images that were highly arousing and negative may have recruited the most elaborative processing (largest LPP) followed by unrelated neutral images, which may have been processed as conceptually distinct from one another. This is supported by studies that suggest incongruity with previous images in the list can lead to an increased LPP (e.g., Herring, Taylor, White, & Crites Jr, 2011). This would also explain why unrelated neutral stimuli had a larger LPP and P300 Dm effect than related neutral stimuli. Lastly, related neutral images received the least elaborative processing, as semantic relatedness offers a mental shortcut. Related stimuli can evoke spreading activation, in which one concept may evoke the activation of similar concepts, necessitating less processing than unrelated stimuli (Collins & Loftus, 1975). Importantly, this suggests the increased LPP evoked by negative stimuli as compared with neutral stimuli cannot be accounted for by the inherent relatedness of negative stimuli. Relatedness instead is associated with a lower LPP, indicating decreased elaborative processing.

Heart Rate

Distinctiveness and relatedness also interacted to modulate heart rate changes. When stimuli occur at a predictable rate, any resulting increases in heart rate upon stimulus onset likely reflect both an increase in arousal response (Bradley & Lang, 2007) and an increase in attention or cognitive effort (Jennings & Hall, 1980). Because of this, heart rate data can be difficult to interpret. However, these results suggest a physiological change dependent on both distinctiveness and relatedness. In pure lists, changes in heart rate did not differ between image categories. However, for mixed lists, there were changes between image types reflecting the pattern found in the LPP. The largest change in heart rate was for negative, then unrelated neutral, and then related neutral images. This suggests further evidence for prioritization in mixed lists.

Conclusion

The current results indicate enhanced arousal and attention in EEM cannot be explained by the inherent relatedness of emotional stimuli. Instead, emotional stimuli may benefit from a double mnemonic boost of attention at encoding and relatedness at recall. In addition, distinctiveness in mixed lists may lead to forced prioritization and differential processing, selecting more salient (negative) and incongruent stimuli (unrelated neutral), at the expense of more easy-to-process stimuli (related neutral).

Additional Information

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Data Availability Data are available here https://osf.io/4kj6f/.

Conflict of Interest The authors declare that they have no conflict of interest.

Ethical Approval This study was approved by the Wofford College Institutional Review Board and the study was performed to ethical standards as laid down in the 1964 Declaration of Helsinki.

Informed Consent Informed consent was obtained from all research participants. No experiments were pre-registered. Consent to publish is given.

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The submitted work has not been published previously and is not being considered for publication elsewhere.