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RESEARCH ARTICLE

Memory and event-related potentials for rapidly presented emotional pictures

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Abstract Dense array event-related potentials (ERPs) and memory performance were assessed following rapid serial visual presentation (RSVP) of emotional and neutral pictures. Despite the extremely brief presentation, emotionally arousing pictures prompted an enhanced negative voltage over occipital sensors, compared to neutral pictures, replicating previous encoding effects. Emotionally arousing pictures were also remembered better in a subsequent recognition test, with higher hit rates and better discrimination performance. ERPs measured during the recognition test showed both an early (250–350 ms) frontally distributed difference between hits and correct rejections, and a later (400–500 ms), more centrally distributed difference, consistent with effects of recognition on ERPs typically found using slower presentation rates. The data are consistent with the hypothesis that features of affective pictures pop out during rapid serial visual presentation, prompting better memory performance.

Keywords ERP · Emotion · Picture · Memory · RSVP · Recollection · Familiarity

Introduction

In a rapid serial visual presentation (RSVP) paradigm, stimuli are presented at rapid rates resulting in a perceptual array consisting of fleeting images. To explore how affective features of picture stimuli affect encoding Junghöfer et al. (2001) presented pictures that alternated between those rated high and low in emotional arousal at a rate of 3 or 5 Hz. Event-related potentials (ERPs) measured during the RSVP sequence resulted in a pronounced difference between more and less emotionally arousing pictures that was maximal 250 ms after picture onset, with emotionally arousing pictures prompting a marked negative deflection at sensors over the occipital cortex. A subsequent study (Peyk et al. 2009) replicated this effect using faster presentation rates (up to 12 Hz) and demonstrated that the latency of the enhanced negativity remains constant, irrespective of the speed at which pictures are presented. One hypothesis is that the occipital negative deflection indexes enhanced processing of the affective images in the rapid visual stream.

If the occipital negative deflection measured during RSVP indicates enhanced encoding, then a prediction is that pictures prompting larger early negative potentials should be remembered better in a subsequent memory test. Such a finding would provide converging evidence that emotional stimuli attract enhanced attention as indicated in studies finding effects of emotion on attentional blindness (Anderson and Phelps 2001; Anderson 2005), dual task performance (Bradley et al. 1999), memory performance (Bradley et al. 1992), and other indices of attention allocation. Previous RSVP studies using neutral stimuli have found that, while individual items can be accurately identified during rapid presentation, later memory performance is poor (Potter 1976). If the ERP differences measured during RSVP encoding indicate better identification of emotionally arousing pictures, one prediction is that subsequent memory performance for emotionally engaging pictures should be enhanced as well.

In the current study, we tested this hypothesis by presenting a sequence of pictures at a rapid rate, followed immediately by a recognition test for a single target picture

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from the sequence. If emotionally arousing pictures are indeed better detected during rapid serial visual presentation, we expected better recognition performance for pictures high in emotional arousal, compared to those rated low in emotional arousal. When recognition memory following rapid picture presentation has previously been investigated, a decline in performance is typically found as the number of recognition test items increases (Potter et al. 2002). To avoid item interference, we tested a single picture following each input sequence. Based on the data reported by Potter et al. (2002), we expected that the hit rate when testing one item from the sequence would be above chance, but not perfect, which would allow us to assess effects of emotional arousal on recognition performance.

We investigated several variables that could potentially affect RSVP recognition memory. For instance, later recognition of a briefly glimpsed picture may rely on perceptual features, on conceptual features, or on both (Potter et al. 2004). To evaluate these effects, we co-varied the perceptual and conceptual similarity between a picture presented during RSVP and its subsequent test in four different groups of participants. One of the RSVP pictures, designated as a critical picture, constrained the features of the test picture used in the recognition task. *Perceptual similarity* was manipulated by always presenting the input sequences in color and varying whether the test picture was presented in color (matching its presentation in the RSVP sequence) or in grayscale. *Conceptual similarity* was manipulated by varying whether a new test picture and the critical input item were similar or unrelated in semantic content. These two variables were crossed to produce four different between-subject conditions.

Previous studies have suggested that color can play a role in recognition performance. For example, Oliva and Schyns (2000) showed that colored blobs can affect the recognition of scenes without prior recognition of the objects in the scene, and Gegenfurtner and Rieger (2000) found that when recognizing objects in natural scenes, color information contributes to both the sensory (coding) and cognitive (representation) features of information processing, leading to faster and better recognition memory. Furthermore, accurate recognition may be disrupted by new test pictures that are semantically related to the input picture. Potter et al. (2004) found that when lures (“new” items) were conceptually similar to targets, the percentage of distractors wrongly recognized as old pictures was higher than when non-semantically related distractors are presented. To the extent that perceptual or conceptual relatedness influence later recognition, we expected these variables to impact correct discrimination of old and new pictures in the recognition test.

Dense array (257 channels) event-related potentials were recorded to elucidate the brain mechanisms in RSVP memory performance, as well as the relationship between brain measures of emotional arousal and recognition. In fact, despite a wealth of studies exploring recognition performance following RSVP, the use of ERPs as an index of recognition memory is novel in the RSVP paradigm. On the other hand, many ERP studies have explored recognition memory for items presented at a slower rate and have found reliable ERP differences for trials producing hits and correct rejections (Rugg 1995). In general, hits elicit more positive-going ERPs than correct rejections, with two spatially and temporally dissociable components typically reported (Curran and Cleary 2003; Duarte et al. 2004). An early component (onset around 200 and 300 ms post stimulus with a frontally distributed topography) has been hypothesized to reflect memory decisions that are primarily based on familiarity, whereas a later component (onset around 400–500 ms post stimulus, with a more posteriorly distributed topography) is hypothesized to reflect explicit recollection, or conscious memory for the occurrence of the test item (Mecklinger 2000; Friedman and Johnson 2000; Curran 2004).

Both the temporal and the spatial distribution of these differences seem to be influenced by the nature of the items used in the memory task. When pictures (instead of the more common verbal stimuli) are used, the onset of each component can be somewhat earlier, and the topographical distribution of the later difference is not as posterior as found for words (Schloerscheidt and Rugg 1997, 2004). In the current study, we explored whether rapidly presented pictures show similar recognition effects as found when pictures are presented at encoding at much slower presentation rates, and, if so, how emotional arousal, perceptual similarity and conceptual relatedness affect these components following rapid presentation.

We also re-evaluated the finding that emotionally arousing pictures prompt a larger negative potential at encoding over occipital sensors, as originally reported by Junghöfer et al. (2001). In that study, when pictures were presented at 333 ms each, the maximum difference between pictures rated high or low in arousal was observed around 250 ms after picture onset. For pictures that were presented at an even faster rate in that study (i.e., 200 ms per picture), the difference in ERPs also appeared at 250 ms, apparently moving the effect into the beginning of the next picture. In the current study, pictures were presented at a fast rate (184 ms), as has been employed in RSVP memory studies, and we expected differences between pictures high and low in emotional arousal to similarly be apparent in the beginning of the next picture.

Method

Participants

Participants were 70 students from the University of Florida who participated in partial fulfillment of a research requirement in their General Psychology class. Because of equipment problems or presence of artifacts in the EEG recordings, the final number of participants used in analyses of the data was 60 (31 female).

Materials and design

Encoding sequences consisted of 8 pictures presented at 5.4 Hz (184 ms per picture), followed, after 1-s, by a single test picture (see Fig. 1 for a schematic representation of the experimental design). In each sequence, pictures alternated between those high and low in emotional arousal, following Junghöfer et al. (2001). For design purposes, only one picture in each input sequence was tested. This picture was designated as the critical picture. The critical picture constrained the features of the subsequent test picture. The critical pictures were constructed in 64 sets of three pictures. In each triplet, the three pictures were similar in semantic content (e.g., 3 pictures of babies). Of the 64 triplets, 32 included contents that are typically rated high in emotional arousal, with 4 each from the semantic categories of adventure, erotic couples, erotica, sports, accidents, animal threat, human threat, mutilation, and 32 were rated lower in arousal, with 4 each from the 8 categories consisting of families, food, objects, nature, contamination, illness, loss, pollution. Of the 192 pictures in these triplets, 128 were presented in the input sequences; the remaining 64 served as "new" items in the recognition test, balanced across the 16 semantic categories.

On half (64) of the encoding trials, the test picture was identical to the critical picture ("old"), and on half (64) of the trials, the test picture was a distractor ("new") of the same hedonic valence (pleasant or unpleasant) and level of arousal as the critical picture. All of the test pictures (i.e., both old and new) were selected from the International Affective Picture System[1] (Lang et al. 2005).

[1] The IAPS pictures presented as test picture (i.e., old or new exemplars) were: Adventure: 8170, 8180, 8490, 8370, 8161, 8178, 8496, 8400; Erotic couples: 4650, 4680, 4690, 4660, 4653, 4669, 4666, 4687; Erotica: 4220, 4290, 4490, 4520, 4002, 4232, 0445, 0441; Sports: 8210, 8470, 8190, 8200, 8211, 8090, 8191, 8080; Accidents: 9920, 9910, 9050, 9600, 9911, 9912, 9622, 9620; Animal Threat: 1930, 1300, 1050, 1120, 1932, 1525, 1070, 1052; Human Threat: 3530, 6260, 6510, 6350, 3500, 6230, 6243, 6550; Mutilation: 3110, 3130, 3060, 3080, 3140, 3120, 3000, 3069; Families: 2360, 2070, 2080, 2340, 2395, 2071, 2058, 2341; Food: 7470, 7350, 7400, 7330, 7480, 7450, 7410, 7270; Objects: 5530, 5510, 7040, 7030, 5534, 5533, 7050, 7034; Nature: 5000, 5760, 5891, 5780, 5020, 5250, 5593, 5711; Contamination: 9320, 7360, 7380, 9300, 9301, 7359, 9373, 9570; Illness: 3300, 3230, 2710, 3180, 3350, 3102, 2752, 3181; Loss: 9220, 2205, 9421, 2900, 9265, 2141, 9530, 2810; Pollution: 9110, 9330, 9830, 9120, 9090, 9342, 9471, 9520. Approximately two-thirds of the pictures presented at encoding were selected from the IAPS; the remaining were selected from other sources that included exemplars in the specific semantic categories (e.g., sports, babies, etc.).

For participants receiving new distractor items that were *semantically related* to the critical picture ($n = 28$; 14 viewing test pictures in color and 14 in grayscale), the three pictures in each triplet (e.g., three pictures of babies) were distributed across "old" and "new" trials as follows: on the "old" trial for each triplet, one picture from the triplet served as both the critical input item and the "old" test item. On the "new" trial, the remaining two pictures served as critical input item and the "new", related test item, respectively (see Fig. 1). Across participants, the pictures were counterbalanced such that the first and second pictures in each triplet were equally often "old" or "new" test pictures; the third picture in each triplet always served as the input item on "new" trials.

For participants receiving distractor items that were *semantically unrelated* to the critical picture ($n = 32$; 16 viewing test pictures in color and 16 grayscale), the three pictures in each triplet were distributed across "old" and "new" trials as follows: again, on the "old" trial for each triplet, one picture from the triplet served as both the critical input item and the "old" test item. The remaining two pictures served as (1) a critical picture on one trial (subsequently tested with a new item from a different semantic category, (see Fig. 1) (2) as a new, unrelated test item on a different trial (in which the critical item was from a different semantic category). New test items on each trial were of the same pleasure and arousal as the critical picture: only the semantic content varied.

After selection of these triplets, the remaining pictures ($n = 769$) in the IAPS were divided into pictures that were high or low in emotional arousal based on a median split of the IAPS arousal ratings (Lang et al. 2005). Then, 128 sequences were created in which the pictures in each sequence alternated between pictures high and low in emotional arousal. Of these 128 sequences, 64 input sequences started with an emotionally arousing picture, whereas the remaining 64 sequences began with a low arousal picture (see Fig. 1). In each input sequence, there was only one exemplar from any of the 16 semantic categories. For each type of sequence (e.g., high–low–high etc., low–high–low, etc.), half (32) were subsequently tested with a picture from the input sequence ("old"), and half (32) were tested with a new picture. For all input sequences, the 8th picture was always an outdoor scene (low arousal) to provide a constant baseline from which to assess ERPs to the test picture.

The critical picture was placed in the fourth serial position in each of the 128 input sequences**.** To offset predictability, an additional 32 foil trials (16 "old", 16 "new") were included in which either the second or seventh picture of the input sequence was tested. Data from the foil trials were not used in any analyses.

The 160 trials were arranged in 16 sub-blocks of five trials each. Within each sub-block, there were two "old" (one

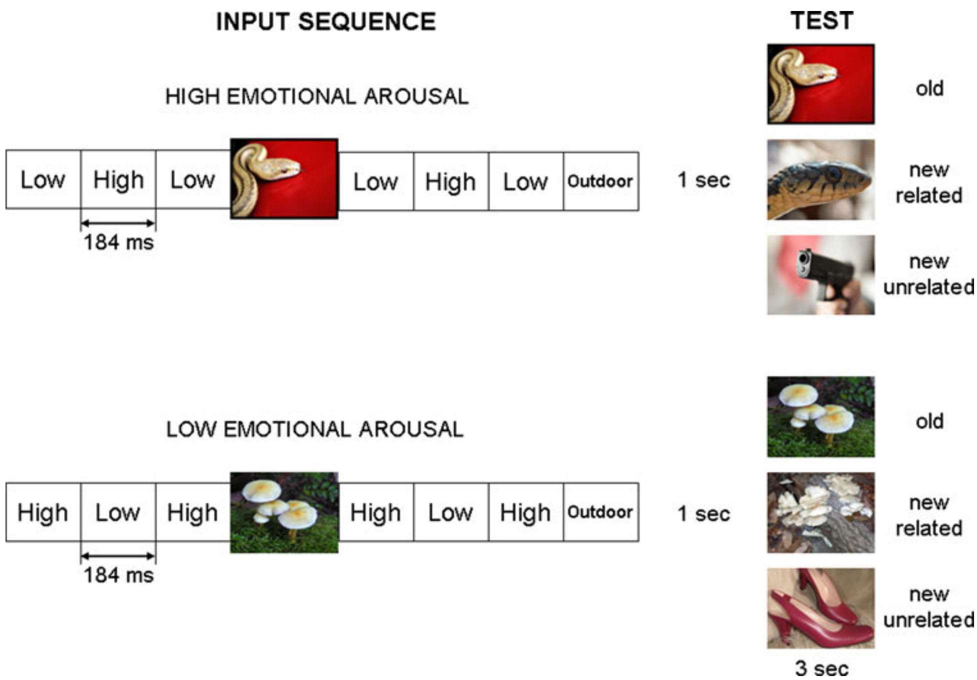

Fig. 1 Schematic representation of the experimental design. Input sequences were 128 sets of 8 pictures that alternated presentation of high- and low-arousal color pictures in a rapid sequence (184 ms each). For each input sequence, a critical target constrained the immediate (1 s retention interval) recognition test of a single item from the series: Either the critical picture itself was presented ("old"; 64 trials), or a new picture was presented that was either the same semantic content as the critical picture ("new related"; 32 trials) or different semantic content ("new unrelated"; 32 trials). Examples are given for a high-arousal critical target (*upper panel*) and a low-arousal critical target (*lower panel*). In one group of participants, the test pictures were presented in color (matching the input sequence); in one group, the test pictures were presented in *grayscale*. Because IAPS pictures are for laboratory use only and can not be published, the specific pictures in this figure simply illustrate the semantic content of pictures used in the experiment, and were obtained from a royalty-free website (licensed as Creative Commons by Lisa Batty, Kim Fleming, Chuck Rogers, Daniella Koontz)

high and one low in emotional arousal), two "new" trials (one high and one low in emotional arousal) and one foil trial. The order of the trials was randomized within each sub-block, and the presentation order of the sub-blocks was randomized for each subject.

Presentation of stimuli and response collection were controlled by E-PRIME software running on a PC. Pictures were presented on a 17 in. screen at a viewing distance of 80 cm.

Procedure

Each trial began with the words "Get Ready" presented on the screen for 1000 ms. followed by a 500-ms presentation of a fixation cross in the center of the screen. Then, the eight pictures in the input sequence were presented, each picture for 184 ms without any inter picture interval. One-second following the offset of the final picture, a single test picture was presented for 3 s. The participant decided whether the test picture had been presented in the input sequence and pressed a button indicating "yes" or "no". Hand of response was counterbalanced across participants. After 3 s, the test picture disappeared and the next trial began.

Both speed and accuracy were emphasized in the recognition instructions, and 5 practice trials preceded the experiment. Following this, two blocks of 80 trials were completed, with a 5-min break between blocks.

EEG data acquisition

EEG was continuously recorded at 250 Hz using a 257 sensor system (Electrical Geodesic Inc., Eugene, OR), filtered at .01 Hz and 100 Hz. Scalp impedance of each sensor was kept below 80 Kohm. Data were acquired referenced to Cz, and the average reference was calculated off-line.

The EEG data were reduced and analyzed using Brain Vision Analyzer version 1.05. For artifact rejection, the recording was segmented into 128 4200 ms epochs beginning 200 ms before the presentation of the fixation cross to 1500 ms after the presentation of the test picture. A software filter (.03–30 Hz 12 db/Oct slope) was applied offline to the data, bad channels were interpolated using 6 neighbor channels and the average reference was calculated. Eye blinks were corrected using the Gratton et al. (1983) algorithm implemented in the BrainVision Analyzer software, and segments were inspected for the presence of artifacts.

For analysis of ERPs during the encoding sequences, epochs were selected that encompassed presentation of the critical picture and the picture following it. The baseline was computed across both of these pictures, and epochs were averaged as a function of whether the critical picture was high or low in emotional arousal. Following previous studies (e.g., Junghöfer et al. 2001), ERPs were averaged over 77 posterior (occipital and parietal) sensors to assess encoding effects.

For the recognition test, each ERP epoch included a 200-ms baseline prior to the onset of the test picture, and 800 ms following the test picture. These epochs were averaged for each participant on the basis of memory performance (hits, correct rejections) and picture emotional arousal (high, low).

Results

Memory performance

The percentage of hits (correct responses of "yes" to "old" items) and correct rejections (correct responses of "no" to "new" items) were computed for each participant, and a bias-free index of correct discrimination was computed (i.e., hits—[1—correct rejections]; Snodgrass and Corwin 1988; 0 = chance, 1 = perfect discrimination). Each dependent measure (i.e., hits, correct rejections, and discrimination score) was analyzed in a separate ANOVA using the emotional arousal of the test picture (high, low) as a repeated measures variable, and perceptual similarity (color, grayscale) and conceptual similarity (same, different content) as between-subject variables. Table 1 lists the means for each analysis.

Discrimination index

As expected, discrimination performance for rapidly presented pictures was significantly better than chance, $t(1,59) = 39.03$ $P < .001$. Thus, despite the rapid speed of presentation, participants were able to significantly discriminate old from new pictures. A significant interaction between emotional arousal and semantic similarity, ($F(1,56) = 6.83$, $P < .05$) indicated that memory for emotionally arousing pictures was affected by the semantic similarity between the critical picture and the test item. As illustrated in Fig. 2, discrimination performance was significantly better for emotionally arousing, compared to low arousal, pictures when the new test picture was from a different semantic category than the critical input item, ($F(1,56) = 9.29$, $P < .01$). This was true regardless of whether the test picture was presented in color or in grayscale (see Table 1). On the other hand, when new test items were semantically related to the critical pictures presented in the input sequence, there was no difference in correct discrimination performance for high- and low-arousal pictures.

Table 1 Percentages (SEM) of hits and correct rejections and mean discrimination scores (SEM) for high- and low-arousing pictures when new test pictures were semantically related or unrelated to the input item and presented in *color* or *grayscale*

Dependent measure	Semantically unrelated		Semantically related	
	High	Low	High	Low
Hits				
Color	.81 (.02)	.78 (.02)	.81 (.03)	.75 (.04)
Grayscale	.76 (.05)	.71 (.04)	.75 (.04)	.68 (.03)
Correct rejections				
Color	.83 (.03)	.79 (.02)	.61 (.04)	.72 (.03)
Grayscale	.84 (.03)	.81 (.03)	.71 (.03)	.77 (.04)
Discrimination score				
Color	.64 (.01)	.57 (.02)	.41 (.02)	.46 (.02)
Grayscale	.60 (.03)	.52 (.02)	.46 (.02)	.45 (.03)

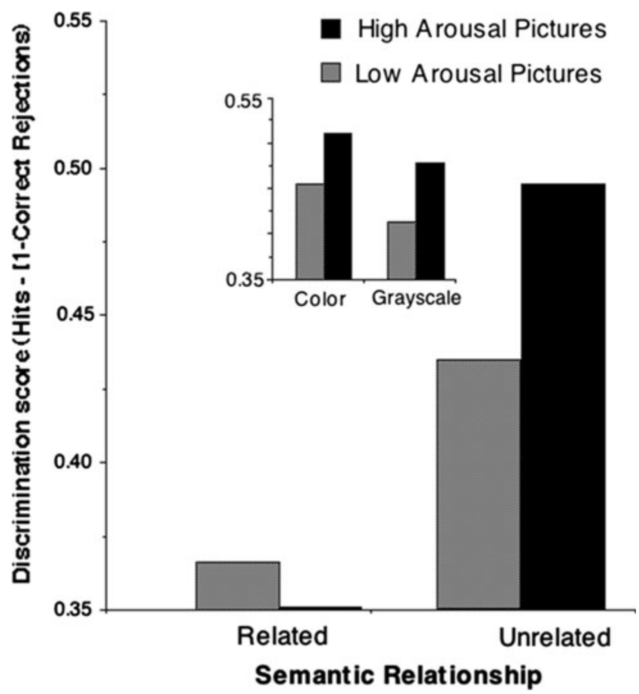

Fig. 2 Discrimination performance for high- and low-arousing pictures when the new test items are semantically unrelated or related to the input picture. The *inset* illustrates discrimination performance when the test pictures are presented in *color* or in *grayscale* for the semantically unrelated group

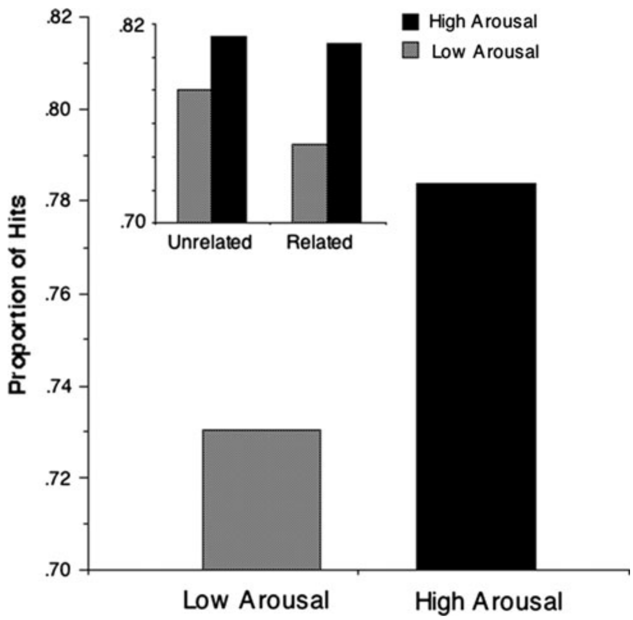

Fig. 3 Proportion of hits for high- and low-arousing pictures. The *inset* shows the proportions of hits for high- and low-arousing pictures when the new test items were semantically unrelated or semantically related to the input picture

To shed light on these effects, hits and correct rejections to "old" and "new" test pictures alone were further analyzed.

Hits

Emotionally arousing test pictures that were present in the input sequence ("old" pictures) were recognized better than old pictures rated lower in arousal, as illustrated in Fig. 3, resulting in a significant elevation in hit rate for arousing pictures, $F(1,56) = 12.96$, $P < .001$. This facilitation in recognizing previously presented arousing pictures was identical regardless of whether new items were semantically related to the input items or not (see inset), as expected. These data support the hypothesis that emotionally arousing pictures are detected better during rapid presentation than low-arousal stimuli. A marginal main effect of perceptual similarity, $F(1,56) = 3.8$, $P = .056$, indicated that the hit rate was slightly higher when the test picture was the same in terms of color (.79), compared to when the test picture was presented in grayscale (.73), but this did not vary with emotional arousal.

Correct rejections

For new test pictures, however, the proportion of correct rejections was affected by semantic similarity, as evidenced by a main effect of semantic similarity, $F(1,56) = 16.03$, $P < .001$, and a significant interaction between semantic similarity and emotional arousal, $F(1,56) = 18.85$, $P < .001$. When a new test picture was semantically unrelated to the pictures in the preceding input sequence (see Table 1), correct rejections tended to be higher for emotionally arousing pictures ($F(1,56) = 3.36$, $P = .073$). On the other hand, when the new test picture was semantically related to an input picture, the correct rejection rate was significantly better for low-arousal pictures, ($F(1,56) = 17.90$, $P < .001$), which is opposite to what is observed for both the hit rate and the discrimination score. Moreover, only the high-arousal pictures showed an improvement in correct rejections when new pictures were semantically unrelated to the input items, $F(1,56) = 27.65$, $P < .001$; for low-arousal pictures, there was no significant difference in correct rejection rate for related and unrelated test pictures. Taken together, these data suggest that highly arousing pictures may have been more similar within a specific category (e.g., erotica) than the low-arousal stimuli, leading to more uncertainty when it was necessary to reject related but new exemplars.[2]

Event-related potentials

Encoding sequences

An ANOVA testing the ERP difference between high- and low-arousal pictures during encoding was computed at each time point[3] following onset of the critical picture. Consistent with previous studies (Junghöfer et al. 2001; Peyk et al. 2009), emotionally arousing pictures prompted a more negative deflection than neutral images. This difference was significant in a window from 236 to 292 ms following onset of the critical picture. This translates into a difference in the ERP in a 52–108-ms time window following onset of the picture immediately following the critical picture, as illustrated in Fig. 4.

[2] This interpretation was supported when the bias was computed (Br, a measure of the criterion adopted to respond in condition of uncertainty) as a dependent variable. A significant interaction between conceptual similarity and arousal ($F(1, 56) = 7.41$, $P < .01$) indicated.that bias ranged from .45 to .47 (slightly conservative although not significantly different from neutral) in all conditions except when distractors were highly arousing and conceptually similar, in which a more liberal bias (Br = .60) was obtained, together with the poorest discrimination. Similar effects (obtained using words as target stimuli) have also been attributed to a higher level of semantic relatedness for emotional words (Maratos et al. 2000), or to a cognitive mechanism designed to avoid to miss potentially relevant items (Windmann and Kutas 2001).

[3] To control for the family-wise error rate, the significance level was determined using a procedure (Maris 2004) in which the data from each subject were randomly allocated to conditions, the F test determined, and the resulting F statistic added to a distribution. Following 8000 permutations, the resulting distribution indicated that an F value greater than 11 produced a $P < .01$, and this F was used to determine significance at each time point.

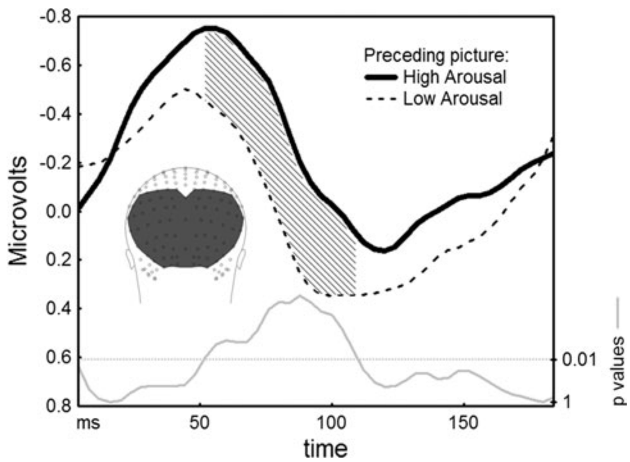

Fig. 4 ERPs (average over 77 posterior electrodes) during the presentation of the fifth input picture as a function of the emotional arousal of the preceding picture. The *gray line* represents the *P* values relative to the comparison between the two conditions. The *shaded area* represents the period of time where the two conditions significantly differ from each other. *Note* for the ERPs positive is down. The *inset* shows the electrodes included in the average

Recognition test

Figure 5 (panel A) illustrates ERPs during the recognition test. As reported in previous studies for materials presented at slower encoding rates (Rugg 1995; Mecklinger 2000), trials associated with hits showed a more positive going ERP than those leading to correct rejections with an earlier onset over the anterior sites and a later onset over more posterior sites. Accordingly, a statistical analysis was conducted for an early time window (from 200 to 300 ms after the onset of the test picture), and for a later time window (from 400 to 500 ms after the onset of the test picture). For the early time window, the average voltage for a group of 20 frontal electrodes was computed for each participant; for the late time window, the average voltage for a group of 21 electrodes located over the centro-parietal areas was computed. In both analyses, emotional arousal (high, low) and performance (hits, correct rejections) were repeated measures, and perceptual similarity (color, grayscale) and conceptual similarity (same, different content) were between-subject variables.

Early time window (200–300 ms post-onset)

Table 2 lists the mean ERPs in the early time window. Similar to effects found using stimuli presented at much slower rates, hits were associated with less negative voltage than correct rejections in the early time window over anterior sensors, $F(1,56) = 21.55$, $P < .001$ Thus, recognition

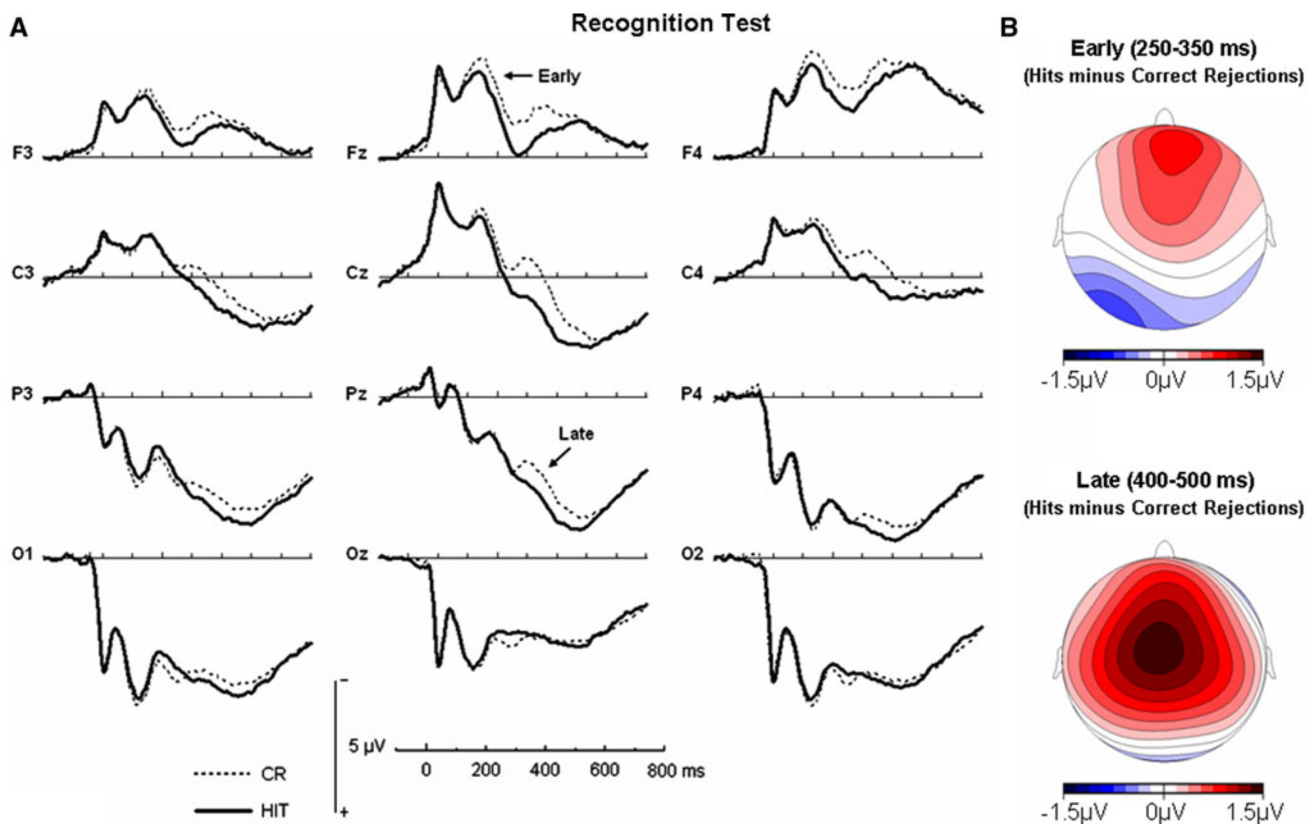

Fig. 5 **a** Grand average ERP at selected electrodes for hits (*solid line*), and correct rejections (*dotted line*). *Note* Positive is *down*. **b** Topographies of the voltage differences between hits and correct rejections in the early (200–300 ms) and late (400–500 ms) time window

Table 2 Mean voltage change (SEM) in the early and late time windows for hits, correct rejections, and their differences when new test pictures were semantically unrelated or related, for pictures high or low in emotional arousal

ERP component	Semantically unrelated		Semantically related	
	High	Low	High	Low
	Frontal sensors, 200-300 ms			
Hits	−2.68 (.40)	−3.17 (.45)	−2.68 (.43)	−3.50 (.48)
Correct rejections	−3.51 (.43)	−4.33 (.47)	−3.33 (.46)	−3.66 (.51)
Memory effect (Hits-CR)	.84 (.29)	1.16 (.31)	.66 (.31)	.16 (.33)
	Posterior sensors, 400-500 ms			
Hits	6.02 (.52)	4.88 (.48)	6.20 (.56)	4.56 (.52)
Correct rejections	4.74 (.47)	3.93 (.51)	4.77 (.50)	3.78 (.55)
Memory effect (Hits-CR)	1.27 (.33)	.95 (.31)	1.43 (.36)	.78 (.33)

memory for pictures presented at extremely rapid rates shows a similar early difference between hits and correct rejections as those found previously when testing memory for material presented at much slower rates (see Fig. 5 panel B). A significant main effect of emotional arousal, $F(1,56) = 16.22$, $P < .01$, indicated less negativity for emotionally arousing, compared to low arousal, pictures. A marginal interaction between performance (hit, correct rejection) and semantic similarity, $F(1,56) = 3.75$, $P = .058$, suggested that this early memory effect was somewhat more reliable when new test items were semantically unrelated to the input item, $F(1,56) = 23.18$, $P < .001$, than when they were related, $F(1,56) = 3.43$, $P = .07$ (see Table 2).

Late time window (400–500)

Hits were associated with more positive voltage over centro-parietal sensors than correct rejections, $F(1,56) = 45.18$, $P < .001$, replicating effects found previously when testing recognition memory for stimuli presented at much slower rates(see Fig. 5 panel B). A significant main effect of emotional arousal, $F(1,56) = 34.90$, $P < .001$, indicated greater positivity for emotionally arousing, compared to low-arousal, pictures. On the other hand, this difference was found regardless of whether the picture was new or old. Thus, this effect appears to represent the late positive potential that is usually elicited by the presentation of emotional images, rather than to represent a memory difference. There were no differences in the size of the memory effect (hits-correct rejection) as a function of emotional arousal, perceptual similarity, or semantic similarity.

Discussion

Emotionally engaging pictures presented during RSVP prompted a more negative-going potential at encoding over occipital sites, compared to less-arousing pictures in a window approximately 250 ms following picture onset, replicating previous ERP findings that showed the time invariance of this effect irrespective of the presentation speed (Junghöfer et al. 2001; Peyk et al. 2009) More importantly, a subsequent recognition test indicated that emotionally arousing pictures were also recognized better than low-arousal stimuli, with a significantly greater proportion of hits for emotionally engaging pictures, and better memory discrimination performance, particularly when new test pictures were not semantically similar to the input items. Heightened memory performance for affectively arousing pictures supports the hypothesis that these pictures are detected more frequently than less-arousing pictures when presented at rapid rates, and that the heightened negative ERP potential at encoding may mark attention capture by features of motivationally relevant stimuli. Whereas some have interpreted the heightened negativity for emotional pictures during rapid picture presentation as reflecting a similar ERP component as found during slow picture presentation (i.e., the EPN, early posterior negativity; Schupp et al. 2006), there are some differences that might be critical. For instance, whereas the EPN found during slow picture presentation is a positive-going wave that only appears negative after subtracting the emotional from neutral ERP (i.e., less positive for emotional pictures), the enhanced component following RSVP for emotional pictures is a negative-going wave that is more negative for emotional, compared to neutral, pictures (see Fig. 3). Whether the ERP components found during rapid or slow picture presentation reflect the same processes awaits the outcome of future studies that directly compare them.

The facilitation in correct discrimination for emotionally arousing pictures was dependent, to some extent, on whether new test pictures were semantically related to the critical input item. When new test pictures were not semantically similar to the critical input item, a clear effect of emotional arousal indicated better memory performance for these affectively engaging items. On the other hand, when a new test picture was of similar semantic content as one of the input items, participants were more likely to wrongly classify "new" highly arousing pictures (i.e., as "old"), compared to low-arousal pictures, suggesting more confusability for highly arousing pictures. It is possible that the semantic categories used for highly arousing pictures (e.g., erotica) involved exemplars (e.g., nude people) that share more specific features, heightening confusability, whereas exemplars in low-arousal categories (e.g., nature scenes, household objects) were more variable. This could account for greater uncertainty when a new exemplar (with similar features) was presented during the recognition test.

Whether memory performance reflects a match between encoding and test items on the basis of conceptual (e.g., semantic) or perceptual features cannot be determined from these data. Although the data are consistent with a hypothesis that conceptual information is encoded (even at this rapid rate), it is also possible that a match in lower level perceptual features mediates the poorer performance for new highly arousing pictures from the same content category. Although another physical characteristic of the pictures—color—did not differentially influence memory decisions for high- and low-arousal pictures, color cues are not diagnostic with regard to picture content (e.g., both pizza tomato sauce and mutilations share a red hue). Regardless of the specific reason for differences in correct rejections of new pictures, recognition of pictures actually presented in the input sequences (i.e. hits) was always better for highly arousing stimuli.

Analysis of the ERPs elicited during the recognition test evidenced a voltage difference between hits and correct rejections that is consistent with ERP differences found in recognition memory for items presented at much slower rates (Rugg 1995; Mecklinger 2000; Schloerscheidt and Rugg 1997, 2004). Thus, despite the greatly speeded rate at encoding, trials resulting in hits elicited more positive going waves compared to trials producing correct rejections, and this difference was present early over frontal sites and later over more posterior fronto-central areas. In the memory ERP literature, the early frontal differences are hypothesized to reflect memory decisions primarily based on item familiarity (Duarte et al. 2004; Curran 2000). Our data are consistent with this interpretation, as the ERP familiarity effect was stronger in the groups who received new pictures that were semantically unrelated to input items. For these participants, memory decisions could be accurately based on sheer familiarity (i.e., semantic content) as new test items never shared semantic information with pictures in the immediately preceding input sequence.

Assuming that the late memory component indexes successful recollective experience (Rugg 1995; Mecklinger 2000; Curran 2004), the differences between hits and correct rejections in this component, reliably present regardless of semantic relatedness, suggest that recognition judgments also reflected retrieval of specific information about the prior occurrence of the picture. Although the statistical analyses for the late time window were performed on a group of parietal electrodes, the topographical distribution observed for this effect seems to indicate a voltage topography somewhat more centrally distributed than the parietal old/new effect often observed in the literature. This difference is most likely due to the fact that in our experiments pictures instead of verbal material were used. In fact when the ERPs elicited by words and pictures in a recognition task were directly compared (Schloerscheidt and Rugg 1997, 2004) an earlier onset of both the early and the late components for pictures was noted, as well as a less parietally distributed topography for the late effect.

Regardless, the data indicate similar early and late differences between hits and correct rejections in ERPs that are found when recognizing visual stimuli presented at much slower rates, suggesting that similar recognition processes are operating regardless of the presumably impoverished encoding environment during RSVP. Our findings also support the idea that similar retrieval processes may underlie long- and short-term picture recognition (Danker et al. 2008): unlike previous studies which presented many more items at encoding and a much longer delay prior to recognition testing, in our experiment only 1-s elapsed between the end of the short (8 picture) encoding sequence and the presentation of the test picture, an interval not sufficient to allow long-term memory consolidation.

The old–new difference in late ERPs was similar for pictures of high and low arousal. Nonetheless, a main effect of emotional arousal for this late potential indicated that emotionally arousing pictures, regardless of whether they were old or new, prompted greater positivity than less-arousing pictures in this time window. This late positive potential when viewing emotionally arousing pictures is a well-replicated phenomenon (Cuthbert et al. 2000; Keil et al. 2002) and has been interpreted as indicating heightened attention to motivationally relevant pictures. In the current study, both old and new test pictures that were emotionally engaging prompted this enhanced late positive potential at the recognition test, indicating enhanced processing, but was unrelated to correct memory performance. Nonetheless, this positive potential was also heightened for hits, compared to correct rejections, indicating an independent memory effect occurring in the same time window over the same sensors.

Unlike the behavioral data, neither of the ERPs that reflect memory effects (e.g., hits minus correct rejections) evidenced strong differences due to emotional arousal. The discrepancy between the ERP and behavioral measures is most likely due to the specific data contributing to the two analyses. For the ERP data, only trials in which participants correctly recognized old ("hits") and new ("correct rejection") pictures were used. On these correct trials, the processes contributing to accurate memory performance appear to be similar for both high- and low-arousal pictures. Conversely, the behavioral data includes trials in which participants made errors, finding, for instance, that the probability of correctly recognizing "old" high-arousal pictures is more accurate (i.e. more hits) than correctly recognizing "old" low-arousal pictures. Whereas it is the difference in error rates that prompts the difference in behavioral performance for high- and low-arousal pictures, these proportions are lost in the ERP analysis and are difficult to assess without inducing a much higher error rate than in the current study. Future studies could be designed to increase the false alarm rate, making an assessment of emotion and ERPs in the RSVP paradigm more tractable.

In summary, the results are consistent with the hypothesis that features of affectively engaging stimuli pop out of a rapid visual stream, with this facilitation in encoding apparent in subsequent recognition performance. This conclusion converges with that from attentional blink (AB) studies, in which the report of a target stimulus within a stream of rapidly presented items suffers if another target immediately (200–500 ms) precedes it. Several studies (e.g., Anderson and Phelps 2001; Ihssen and Keil 2009) have found that this "attentional blink" is reduced if the second target is an emotionally arousing word, suggesting it receives heightened processing. Unlike the AB paradigm, the RSVP paradigm utilized here requires attention to all the items in the rapid stream. Intraub (1984) reported that the probability of correctly recognizing an item within a rapid stream increases when attention is intentionally oriented toward it. We have suggested that emotional stimuli *naturally* engage selective attention, in the absence of specific tasks or explicit instructions, which is mediated by activation of the fundamental appetitive or defensive motivational systems that are the foundation of human emotion (Lang et al. 1997; Bradley 2009). Both the heightened occipital negativity found for emotional pictures in RSVP and better memory performance suggest that emotional items benefit from enhanced processing, even when presented at rapid rates.

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

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