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Development in the neurophysiology of emotion processing and memory in school-age children

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ABSTRACT

In the adult literature, emotional arousal is regarded as a source of the enhancing effect of emotion on subsequent memory. Here, we used behavioral, electrophysiological, and psychophysiological methods to examine the role of emotional arousal on subsequent memory in school-age children. Five- to 8-year-olds, divided into younger and older groups, viewed emotional scenes as EEG, heart rate, and respiration was recorded, and participated in a memory task 24 hours later where EEG and behavioral responses were recorded; participants provided subjective ratings of the scenes after the memory task. All measures indicated emotion responses in both groups, and in ERP measures the effects were stronger for older children. Emotion responses were more consistent across measures for negative than positive stimuli. Behavioral memory performance was strong but did not differ by emotion condition. Emotion influenced the ERP index of recognition memory in the older group only (enhanced recognition of negative scenes). The findings an increasing interaction of emotion and memory during the school years. Further, the findings impress the value of combining multiple methods to assess emotion and memory in development. Development in the neurophysiology of emotion processing and memory in school-age children.

1. Introduction

Emotion pervades our everyday lives from birth to adulthood. As adults, we demonstrate better memory for emotional than neutral events, words, stories, and scenes ("emotion effect," LaBar and Cabeza, 2006). The effect is attributed to emotional arousal which grants the memory privileged status over multiple phases of memory, including encoding (Hamann et al., 1999), consolidation (Dolcos et al., 2005; McGaugh, 2004; Smeets et al., 2008), and retrieval (Maratos and Rugg, 2001; Weymar et al., 2011). Children's memory for personally experienced emotional events has been well examined, but the emergence and interaction of emotion and memory processes is not well articulated. In the present study, we examined children's response to and memory for emotional and neutral stimuli. The work informs the status of emotion and memory processes in school-age children who are in a period of substantial development in these domains.

A key question regarding emotion-cognition interaction has been the extent to which aspects of the emotional response, such as arousal (intensity or strength of the emotion) and valence (positive or negative), influence a particular cognitive process (e.g., Pessoa, 2008). Examination of emotional memory in adults indicates that emotional arousal influences memory strength. Arousing positive and negative stimuli produce comparable memory enhancement relative to un-arousing neutral stimuli

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(e.g., Hamann et al., 1999), and hormones associated with physiological arousal responses can produce memory enhancement in the absence of an emotional stimulus (Cahill and McGaugh, 1998; McGaugh, 2004). Additionally, emotional valence can influence memory. Some evidence indicates a memory enhancement for valenced but unarousing information (Kensinger and Corkin, 2004), as well as differential network connectivity with the amygdala during successful encoding of negative versus positive stimuli (Mickley Steinmetz et al., 2010).

Investigations in adults examine emotion and memory systems only in their mature form. There is substantial developmental change in emotion and memory networks during the school years that may be expected to impact the nature of the interaction of emotion and memory systems. For instance, he amygdala, a region that regulates multiple facets of the emotional response, shows decreasing emotional reactivity with age, and is increasingly regulated by the prefrontal cortex (PFC; Gee et al., 2013; McRae et al., 2012). The medial temporal lobe regions responsible for conscious memory of personal experiences show increasing functional connectivity with the PFC during this time period, and this connectivity predicts age-related increases in encoding and retrieval performance (Chai et al., 2010; Ofen et al., 2007, 2012). Given these developmental changes, it is reasonable to predict that the school years are a time during which emotion and memory systems become increasingly integrated. The purpose of the present investigation was to inform the integration of the emotional and memory systems in development.

Examinations of children's memory for emotional events have come in different contexts, and yield varied effects of emotion on memory (and false memory, e.g., Brainerd et al., 2010). Substantial research has focused on memory for stressful negative events, ranging in arousal from fear-eliciting video clips, to fire alarms, to invasive medical procedures (e.g., Quas et al., 1999, 2006; Quas and Lench, 2007). This work informs patterns of emotional memory. For example, 2.5–11-year-old children's recall of a devastating tornado was more robust and complete than for neutral events from the same time period (Ackil et al., 2003). Further, 4–8-year-olds' memory for a stressful fire alarm event (Quas et al., 2006) and fearful film clip (Quas and Lench, 2007) was positively related to physiological arousal during encoding. Beyond informing patterns of emotional memory, examinations of stress elucidate the processes and outcomes underlying real-world stressful experience. The work has profound impact from individual well-being to eye-witness credibility. However, to glean a fuller understanding of emotional memory these highly externally valid studies need to be complemented in the literature by studies high in internal validity.

Examination of stress has proven extremely informative, yet studies rarely include comparison of memory for the negative events to positive and neutral events. Experimental control over both the arousal and valence of the stimuli allows for more comprehensive examination of the enhancing effect of emotion on memory. In studies where positive, negative, and neutral stimuli is featured, memory takes a mixed pattern. Seven- to 11-year-olds recalled the actions in emotional stories better than in non-emotional stories after an immediate and 24-hour delay (Davidson et al., 2001). Further, findings from Cordon et al. (2013) suggest that 8–12-year-olds recognize negative scenes better than neutral scenes (though the emotion effect was tested in children and adults combined; Cordon et al., 2013). However, several studies have failed to observe any emotion-related memory enhancement in school-age children (Chen et al., 2000; Howe et al., 2010; Peterson and Bell, 1996). Thus the limited data available to date suggest that school-age children may remember emotional stimuli better than neutral stimuli, but there is variability among findings, and no clear evidence as to when in the memory process emotional arousal plays a role (i.e., at encoding, during consolidation, and/or at the time of retrieval).

A possible explanation for inconsistent findings is variability in assessment of children's emotional responses, and thus variability in the emotional value of the stimuli. In the current research, we used multiple methods of measuring arousal responses to emotional stimuli to validate the emotionality of the stimuli, and examined subsequent patterns of memory. We assessed emotional responses as they unfolded simultaneously over several measures: behavioral measures (ratings), neurological measures (electrophysiology, i.e., event-related potentials, ERP), and physiological measures (heart rate and heart rate variability). The study thus provides a comprehensive measure of emotional arousal, and offers the opportunity to examine the relations between different measures of emotional arousal, and their value as tools to capture emotion responses.

Behavioral measures inform us of the subjective experience of emotion. ERP provides an excellent tool for measuring emotion processing because it is sensitive to real-time emotional arousal during the encoding of an event. A prominent emotion effect in ERP signal is the late-positive potential (LPP). The LPP is a sustained positive-going ERP waveform that begins around 300 ms post-stimulus onset, is maximal over posterior sites, and is larger for emotional (positive and negative) and arousing stimuli versus neutral stimuli (Hajcak et al., 2012). To date, ERP investigations indicate that children as young as 5 years show emotion effects similar to that of adults (e.g., Hajcak and Dennis, 2009; Perez-Edgar and Fox, 2007). Further, ERPs have been informative in studies of emotional memory in adults, with a similar late positive component indexing enhancing effects at encoding (e.g., Dolcos and Cabeza, 2002) and retrieval (e.g., Maratos and Rugg, 2001). The current study is the first ERP investigation of emotional memory in school-age children.

In parallel with ERP, physiological measures can be used to measure emotional responses over time, and can indicate the intensity of emotional responses that may not be available to subjective assessment. Moderately emotionally-arousing stimuli evoke an initial deceleration in heart rate, and an increase in heart rate variability, typically associated with an allocation of attentional resources to the environment (Lang et al., 2008; McManis et al., 2001), as well as sympathetic "fight-or-flight" responses such as pupil dilation and skin conductance responses. Consistent with ERP findings, previous evidence indicates that school-aged children and adults show similar emotional responses in subjective ratings and autonomic physiological activity (Lang et al., 2008; McManis et al., 2001), and engage similar neural circuitry as measured by fMRI (Baird et al., 1999). Thus subjective ratings, electrophysiological and physiological responses offer a fruitful opportunity to further examine interaction of emotional arousal with developmental changes in memory for emotionally-valenced and neutral information.

Here, we used behavioral, electrophysiological, physiological methods to examine children's experience of emotional stimuli and patterns of subsequent memory for the stimuli (measured by behavioral and ERP responses). We tested the hypotheses in school-age children (5–8-year-olds, divided into younger and older groups), who show adult-like emotion responses in ratings and physiology (e.g., Hajcak and Dennis, 2009; McManis et al., 2001, etc.), yet are in a period of developmental change among brain regions making up the emotional memory network. We predicted that across the age groups, we would observe subjective and physiological emotion responses indicative of emotional arousal associated with negative and positive relative to neutral scenes, and that younger children might show heightened emotional reactivity relative to older children, given developmental decreases in reactivity and increases in regulation in school-age children (Gee et al., 2013; McRae et al., 2012). The primary purpose of collecting multiple measures of emotion responses is to provide convergent assessment of the extent to which the stimuli are experienced as emotional. Further, given the argument presented in the adult literature, as well as findings from the stress literature showing enhancing effects of arousal on memory encoding in the early school years (Ackil et al., 2003; Quas et al., 2006; Quas and Lench, 2007), we hypothesized that greater emotional arousal associated with emotional scenes would predict better subsequent memory versus neutral scenes in older children (indicated by larger recognition responses in behavior and ERP for emotional versus neutral stimuli), who have a more developed (and connected) emotion-memory network, than younger children. Because memory for lab-controlled positive and negative emotional stimuli has yet to be examined in children under 7, and limited evidence shows emotion effects on memory in older children, we conducted exploratory analysis of age effects, to determine possible developmental change during this period. Thus we tested the explanatory role of emotional arousal on subsequent memory, with a focus on potential differences between younger and older school-age children.

2. Method

2.1. Participants

Forty-six school-age children participated. Children were divided into two age groups: younger (n = 24, 11 girls; M_{age} = 6.23 years, range = 5.42–7.50 years) and older (n = 22, 13 girls; M_{age} = 8.08 years, range = 7.58–8.92 years). Prior to testing, guardians provided written informed consent and children gave verbal assent. A university IRB approved all methods and materials included in the study.

2.2. Materials and procedure

164 child-appropriate images (55 positive; 53 neutral; 56 negative) were selected from the International Affective Picture System (IAPS; Lang et al., 2008), and a lab-collected set of stimuli of similar content.[2] Images from the IAPS containing weapons, mutilated bodies, or sexual content were excluded from this child-appropriate set. To control for previously reported biases in affective processing of stimuli with humans (Proverbio et al., 2009), within each emotion condition, half of the images included humans and half did not. Before the families came to the lab, thumbnails of all 164 images were sent via email to the guardian to approve presentation of the images (procedure approved by Lang, personal communication).

The study consisted of two sessions separated by 24 hours. During Session 1, electrophysiological (EEG) and psychophysiological (respiration rate, cardiac activity) data were collected as participants viewed positive, negative, and neutral images and participated in a behavioral task to ensure attention to trials. Twenty-four hours later, the participants returned to the lab for Session 2, where EEG data were collected as participants viewed the same positive, negative, and neutral images intermixed with new images of each emotion type, and participated in a behavioral recognition memory task. Immediately after the EEG recording children provided subjective ratings of valence and arousal using the Self Assessment Manikin (SAM; Bradley and Lang, 1994).

EEG data in Sessions 1 and 2 were collected using an Advanced Neuro Technology (A.N.T.) Waveguard EEG cap with 32-shielded Ag/AgCl electrodes (A.N.T. Software B.V., Enschede, The Netherlands; Fig. 2A). Impedances were generally under 5 kΩ. The sampling rate was set at 256 Hz. Data were referenced online to mathematically-linked mastoids. Psychophysiological data were acquired continuously at 1 kHz using the MP150 system and AcqKnowledge 4.0 software (Biopac, Systems Inc.). Electrocardiogram (ECG) data was measured using disposable Ag/AgCl sensors attached in a standard 3 leads montage (Einthoven lead 2 configuration). Respiration was measured as relative changes in thoracic-abdominal expansion, using tension transducer belt wrapped around the lower ribs. The amplifier gain was set to 10, and filters were set to 1 Hz LP, and 0.05 Hz HP.

2.2.1. Session 1

During EEG and physiological recording, children viewed 90 images (30 positive, 30 neutral, 30 negative), presented in a pseudo-randomized order such that no more

[2] Within the negative set, 28 came from the IAPS and 28 from the supplemental set. Within the neutral set, 18 came from the IAPS and 35 from the supplemental set. Within the positive set, 21 pictures came from the IAPS and 34 came from the supplemental set. t-tests were used to compare valence and arousal ratings on negative, neutral, and positive stimuli from the IAPS versus the supplemental set and did not reveal any significant differences on how the two sets were rated (all $ps > .10$).

than two images of the same valence preceded one another. The images and order of presentation were counterbalanced across participants. Five additional positive images were added to the end of each presentation so that the session ended on a positive note. Data analysis did not include the final five positive trials.

To verify attention to the stimuli, participants used a game controller to indicate whether each image depicted a human, or any part of the human body. Before recording, three neutral pictures, which did not appear in the testing phase, were presented as practice trials to establish that children understood how to complete the task. The practice period was repeated as necessary until children demonstrated understanding, then image presentation and data recording began. Images were presented for a total of 6000 ms. For the first 3000 ms, images were framed with a blue border and then a green border for the last 3000 ms. Participants were instructed to attend to the images and to wait until the border changed color before making a button press to indicate if the picture contained a human. A 3500–4500 ms inter-stimulus interval (ISI) followed. Trial structure is shown in Fig. 1. All images were presented in full color at 30.5 cm(h) × 23 cm(w) in size, providing a visual angle of 15.59°(h) × 20.58°(w). Stimulus presentation was controlled using ASA computer software (A.N.T. Software B.V., Enschede, The Netherlands). The task lasted approximately 15 minutes.

2.2.2. Session 2

During EEG recording, participants completed a behavioral recognition task. Participants viewed 60 old images (20 from each emotion condition) and 20 new images from each emotion condition for a total of 120 trials. Images were presented in a pseudo-randomized order such that no more than two images of the same valence preceded one another. Images and order of presentation were counterbalanced such that across participants, all images were used equally often in the old and new conditions. Three additional positive images were added to the end of each presentation so that the session ended on a positive note. Data analysis did not include the final three positive trials.

Participants indicated if they thought each image was old or new, and then rated their confidence in their old/new response (very sure/maybe sure/unsure; Berch and Evans, 1973). Three practice trials were presented to establish that children understood how to complete the task and the practice period was repeated as necessary until children demonstrated understanding (same images as Session 1 practice trials). Once the participants affirmed they understood the instructions, image presentation and data recording began. Images were presented for 2000 ms, then the old/new decision screen for 2000 ms, then the confidence rating screen for 3000 ms. Trials were separated by a 450–650 ms ISI. For children under 7, the old/new decision screen appeared for 5000 ms, then the ISI (no confidence screen because pilot testing indicated that the full task was too burdensome for younger participants). The trial schematic is depicted in Fig. 1. Stimulus presentation was controlled using ASA computer software (A.N.T. Software B.V., Enschede, The Netherlands). The task lasted approximately 17 minutes for all participants.

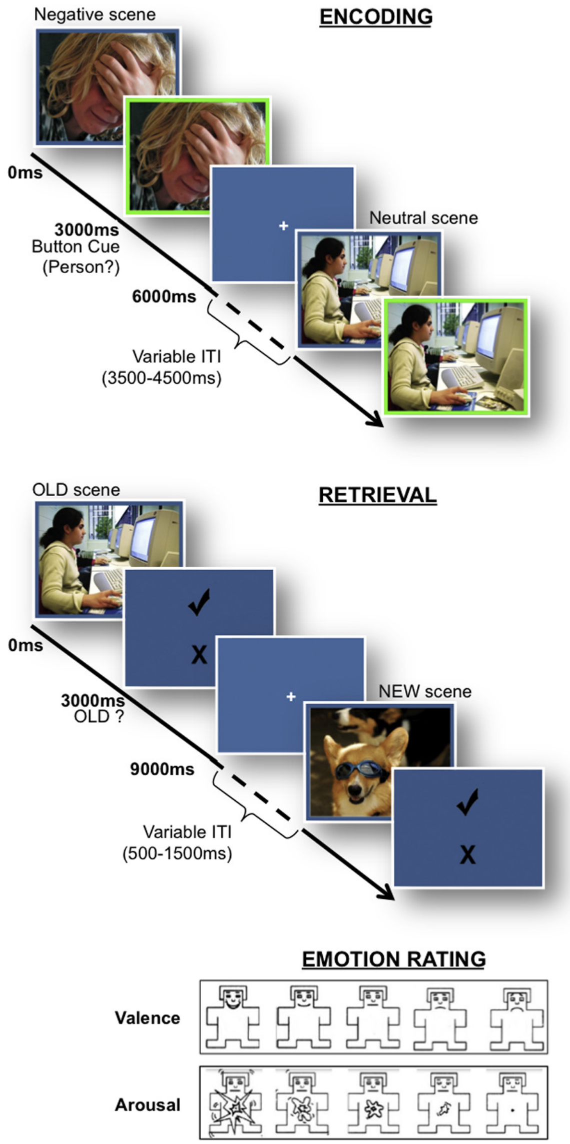

Fig. 1. Behavioral tasks. Trial structure is illustrated for the encoding and retrieval tasks presented during ERP recording. The emotion rating task was conducted using a modified SAM, and administered immediately after retrieval. Encoding and retrieval of emotional images were separated by a 24 h delay. In the retrieval task, the position of the "check" (indicating an old scene) and "x" (indicating a new scene) were counterbalanced across participants. The retrieval task for participants in the younger group is shown here. The older group also viewed a confidence rating prompt displayed for 3000 ms, following the old/new decision screen, not depicted here.

Following ERP recording, participants provided subjective valence and arousal ratings for 30 images (10 from each emotion condition) using a modified Self-Assessment Manikin, shown in Fig. 1 (SAM; Bradley and Lang, 1994). The SAM was abbreviated from the 9-point version of the scale to reduce participant burden on children who had just completed a lengthy task during EEG recording. The modified version consisted of two 5-point scales: one for valence

(1 = very unpleasant, 3 = neutral, and 5 = very pleasant), and one for arousal (1 = very low arousal, 5 = very high arousal).

2.3. Data reduction

2.3.1. Psychophysiological data

Heart rate was indexed using R–R interval, that is, the distance (ms) between heart beats, using the R component of the QRS complex. The QRS complex represents deflections in the ECG waveform corresponding to the depolarization of the right and left ventricles of the heart. R-peaks were identified using an automated QRS identification procedure. The resulting R–R tachogram was examined for cycles outside of a physiologically plausible range (<500 ms or >1000 ms); artifacts in the ECG waveform were corrected by hand. To account for changes in heart rate associated with the baroreceptor reflex, the mean R–R interval was calculated within each respiratory cycle. Respiratory sinus arrhythmia (RSA) was used to index heart rate variability, and was calculated using the peak-valley procedure (Grossman et al., 1990). Respiratory peaks at the inflection point for exhalation onset were identified using an automated classifier. Respiration period was quantified as the distance (ms) between peaks. Respiration amplitude was calculated as the raw amplitude at each peak. To quantify heart rate changes in response to the picture stimuli, a 1000 ms pre-stimulus baseline was subtracted from a 6000 ms post-stimulus epoch, for mean R–R interval, mean R–R interval within respiratory cycles, and RSA. The pre- and post-stimulus windows were selected to replicate previous research on emotional responses to visual stimuli in school-aged children (McManis et al., 2001), and when recording simultaneous ERP responses to visual stimuli (Cuthbert et al., 2000).

2.3.2. ERP data

EEG data were filtered offline using a bandpass filter between 0.1 and 30 Hz with a 24 dB/octave roll-off using Advanced Source Analysis software (A.N.T. Software B.V., Enschede, The Netherlands). All subsequent data processing was completed using EEGLAB 6.03b (Delorme and Maekig, 2004) and ERPLAB 1.0.0.3 (www.erplab.org) operating in Matlab 7.7.0 (MathWorks, Natick, MA, USA). Independent component analysis (ICA) was applied after filtering to identify and remove eye-blink artifact. EEG data was segmented into 2200 ms epochs beginning 200 ms before stimulus onset and ending 2000 ms after stimulus onset. A 200 ms pre-stimulus window was used to correct for baseline activity in each epoch. Trials that were contaminated by deflections that exceeded ±200 μV were excluded from analysis.

Artifact-free epochs were averaged by condition. For the encoding task, there were 3 conditions: negative, neutral, and positive. Two children in the younger group were excluded from analysis because their data contained fewer than 10 artifact-free trials in at least two of the three emotion conditions. Thus in each the older and younger groups, 22 participants were included in analysis. For the recognition task, there were 6 conditions: old and new for each valence (negative, neutral, positive). Only trials on which participants made correct button presses were included, since these represent the cleanest measure of memory (i.e., 'hit' responses on old trials, 'correct rejection' responses on new trials). In the older group, seven participants were excluded due to experimental error ($n = 6$), or attrition after Session 1 ($n = 1$), thus a total of 15 participants were included in analysis. In the younger group, six participants were excluded due to experimental error ($n = 3$), excessive noise in EEG data ($n = 1$), incompletion of the session ($n = 1$), or attrition after Session 1 ($n = 1$), thus a total of 18 participants were included in analysis. Trial counts at encoding and recognition by condition are reported for each age group in Table 1.

Table 1
Trial counts per condition for each age group at encoding and recognition.

Encoding	Older		Younger	
	M	*SD*	*M*	*SD*
Negative	23.00	6.44	18.18	6.64
Neutral	23.68	5.71	17.95	7.77
Positive	22.36	6.77	17.73	6.45
Recognition	**Older**		**Younger**	
	M	*SD*	*M*	*SD*
Negative old	14.47	3.50	10.78	3.26
Negative new	14.13	4.41	12.17	3.78
Neutral old	14.13	3.40	10.56	3.50
Neutral new	14.20	4.41	12.78	3.44
Positive old	14.13	3.60	10.56	4.10
Positive new	13.13	4.73	12.50	3.59

2.4. ERP data analysis

Examination of the data was guided by similar investigations (Dawson et al., 2004; Dolcos and Cabeza, 2002; Hajcak and Dennis, 2009; Maratos and Rugg, 2001; Solomon et al., 2012). Based on the previous research and visual inspection of the ERP waveforms, we identified a sustained positive slow-wave consistent with the late positive potential (LPP) over all scalp sites. For all analyses, effects were examined at posterior clusters primarily, as well as central and frontal clusters (posterior: P7/8, O1/2; central: T7/8, C3/4, CP5/6, CP1/2; frontal: F7/8, F3/4, FC5/6, FC1/2; clusters are depicted in Fig. 2A). For both the encoding and recognition tasks, mean amplitude of the LPP was examined over three time windows (early: 800–1200 ms, middle: 1200–1600 ms, and late: 1600–2000 ms) to investigate the duration and timing of emotion effects. Because preliminary analysis did not indicate effects of site or hemisphere, data were collapsed within each cluster. The LPP is interpreted for deflections toward positive amplitude regardless of value. That is, effects at frontal sites may be negative, but it is the positive deflection that is interpreted. This is consistent with the approach taken in Solomon et al. (2012).

3. Results

Results are divided into two sections: emotion responses and recognition memory. As will become apparent, age effects emerged for all ERP effects.

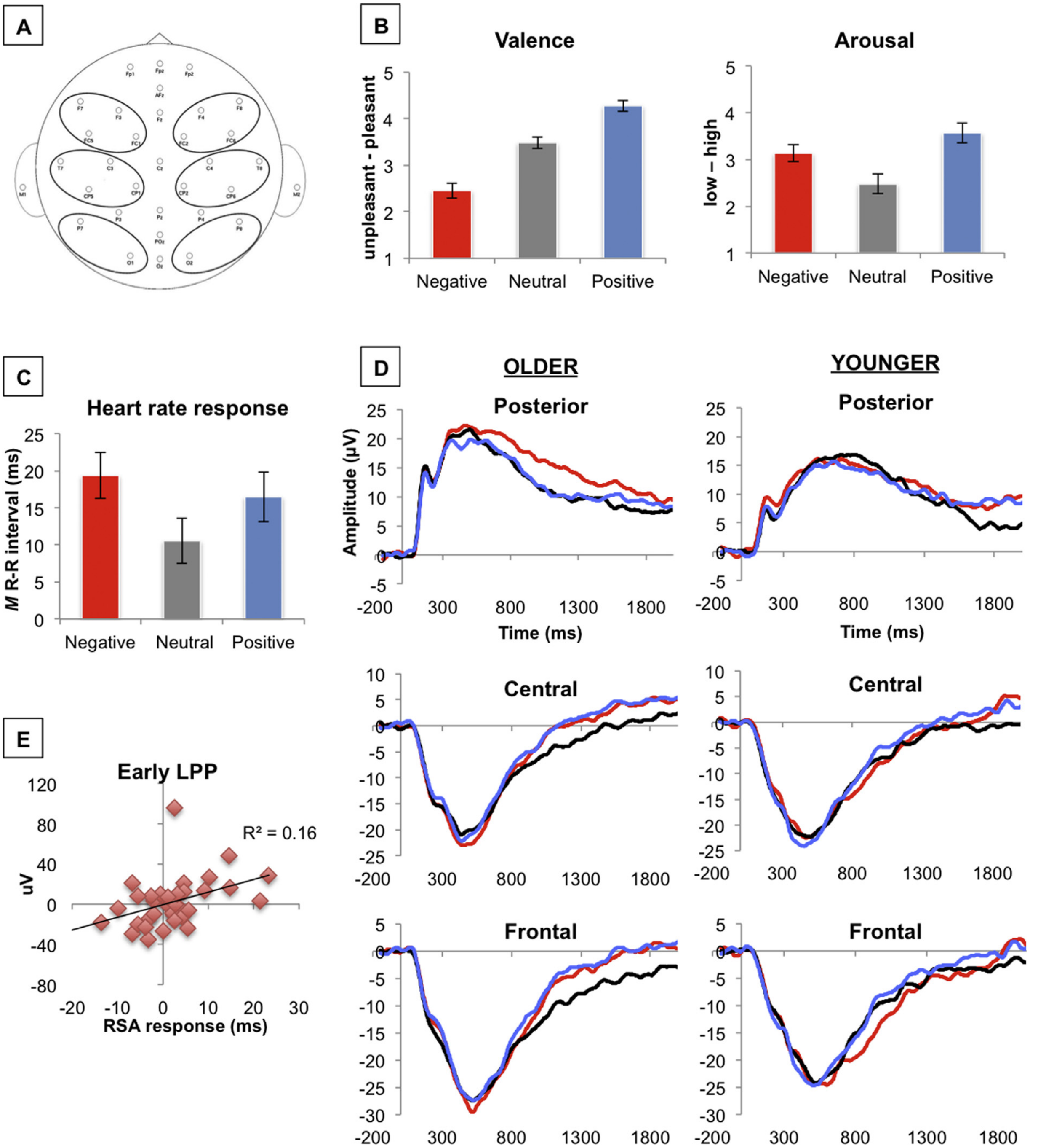

Fig. 2. Effects of negative and positive emotion on subjective, psychophysiological, and ERP responses. (A) Map of electrode locations, using the 10–5 system. Posterior, central, and frontal clusters are circled. (B) Subjective ratings of valence and arousal from the SAM, by emotion condition. (C) Average heart rate response by emotion condition. Note that an increase in R–R interval indicates heart rate *deceleration*, with greater latencies between heartbeats. (D) Older and younger participants' grand averaged waveforms at encoding for posterior, central, and frontal clusters. Negative is plotted in red, neutral in black, and positive in blue. (E) Significant linear correlation between RSA and the mean amplitude of the LPP in the posterior cluster, for negative relative to neutral images. A similar effect was observed in both the early and middle windows. A smoothing algorithm was applied to ERP plots; raw data was used in all ERP analyses. For all graphs, error bars represent ± 1 *SEM*.

For all analyses where a mixed analysis of variance (ANOVA) was calculated, emotion was treated as a within-subjects factor and age as a between-subjects factor. For all analyses of recognition, item status (old, new) was a within-subjects factor. Greenhouse–Geisser corrections were applied in cases of violation of sphericity. Unless noted otherwise, for all post-hoc analyses with multiple comparisons, Bonferroni corrections were applied to the *t*-values.

3.1. Emotion responses

3.1.1. Subjective ratings

Valence and arousal ratings were available for 29 participants ($n = 16$ in the older group).[3] Mean ratings by emotion condition are plotted in Fig. 2B. To examine emotion responses in children's ratings, we calculated 3 (Emotion: negative, neutral, positive) × 2 (Age: younger, older) mixed ANOVAs, for valence and arousal ratings separately. For valence ratings, a main effect of emotion condition was observed, $F(1.38,37.35) = 43.56$, $p < .001$, $p\eta^2 = .617$, with negative images rated as more negative than neutral and positive images, and positive images rated as more positive than neutral and negative images (all $ps < .001$). A main effect of emotion condition also was observed for arousal ratings, $F(2,54) = 12.14$, $p < .001$, $p\eta^2 = .310$. Positive and negative images were rated as more arousing than neutral images ($p < .001$ and $p = .041$, respectively); ratings of positive and negative stimuli did not differ. For both valence and arousal, no effects of age were observed. The results indicate that children experienced the emotional stimuli as emotional and more arousing than the neutral stimuli.

3.1.2. Physiological responses

Physiological measures were analyzed using 3 (Emotion: negative, neutral, positive) × 2 (Age: younger, older) mixed-effects ANOVAs. As reflected in Fig. 2C, emotion condition significantly influenced heart rate responses to the images, $F(2,68) = 4.21$, $p = .02$. R–R interval increased more in response to negative than neutral images, $t(35) = 3.07$, $p = 0.004$) reflecting heart rate deceleration for negative images. The heart rate response to positive images ($M = 16.48$ ms, $SEM = 3.33$) did not differ from the response to neutral or negative images, $ps > .05$. The effect of emotion on heart rate remained when controlling for heart rate variation related to respiratory cycles, $F(2,68) = 4.94$, $p = .01$. There was no significant interaction of emotion condition and age group for heart rate responses, $p > .05$. For RSA, respiration period, and respiration amplitude, there were no significant main effects or interactions (all $ps > .05$).

3.1.3. ERP responses

To examine effects of emotion over the course of the LPP we calculated a 3 (Window: early, middle, late) × 3 (Emotion: negative, neutral, positive) × 2 (Age: younger, older) mixed ANOVA, for mean amplitude in each of the three clusters (posterior, central, and frontal). Because they do not inform the research question, main effects or interactions that do not include emotion are not reported. Post-hoc comparisons by condition were examined at the more stringent level of $p = .025$ following the Sidak–Bonferroni–Keppel correction (Keppel and Wickens, 2004). Waveforms for each cluster are plotted in Fig. 2D. Descriptive statistics for each cluster are reported in Table 2.

3.1.3.1. Posterior cluster. A main effect of emotion condition was observed across all windows, $F(2,84) = 3.60$, $p = .032$, $p\eta^2 = .079$, with responses larger to negative versus neutral images, $t(43) = 2.38$, $p = .022$. Responses to positive images fell in between the two other conditions, and did not significantly differ from them ($ps > .05$). Further, the interaction of window, emotion condition, and age was significant, $F(2.56,107.60) = 2.91$, $p = .046$, $p\eta^2 = .065$. Two-way 3 (Window) × 3 (Emotion) repeated measures ANOVAs were calculated for each age group to further examine the interaction. Among older children, a main effect of emotion condition was observed across all windows, $F(2,42) = 4.04$, $p = .025$, $p\eta^2 = .161$, with larger responses to negative than neutral images, $p = .023$. Responses to negative images also were larger than those to positive, although the effect did not reach significance with the correction, $p = .039$. Responses to positive and neutral images did not differ ($p > .10$). Among younger children, the interaction of window and emotion condition was significant, $F(2.29,48.14) = 3.31$, $p = .039$, $p\eta^2 = .136$. Follow up analysis indicated a main effect of emotion in the late window, $F(2,42) = 3.21$, $p = .050$, $p\eta^2 = .133$, with no significant differences between emotion conditions ($ps > .05$); effects of emotion were not observed in the early and middle windows.

3.1.3.2. Central and frontal clusters. Analyses of both clusters revealed main effects of emotion condition across all windows, $F(2,84) = 3.78$, $p = .027$, $p\eta^2 = .082$, and $F(2,84) = 3.11$, $p < .05$, $p\eta^2 = .069$, for central and frontal, respectively. In both clusters there were significantly larger responses to positive versus neutral images, $ts(43) > 2.45$, $ps < .02$. Responses to negative images fell in between the two other conditions, and did not significantly differ from them ($ps > .05$). Emotion condition did not interact with window or age group.

3.1.4. Relations among ERP, subjective ratings, and psychophysiology

To further probe the nature of emotion responses, we examined correlations between LPP and subjective and psychophysiological responses to negative and positive images. For each participant, responses to negative and positive images were quantified as difference scores (negative or positive – neutral) in LPP mean amplitude, arousal ratings, valence ratings, heart rate response, and RSA. Within the posterior cluster, the response to negative images in the early and middle LPP windows correlated positively with RSA, with a stronger correlation in the

[3] Ratings were not collected for 15 participants due to burdensome session length. Ratings from an additional 2 participants were excluded due to apparent confusion on the part of the participants regarding how to use the scales.

Table 2
Descriptive statistics for mean amplitude responses at encoding across and within windows in the posterior, central, and frontal clusters (panels a, b, and c, respectively). Data within the posterior cluster are separated by age group: younger (<7.5 years) and older participants (>7.5 years).

(a) Posterior	Older		Younger	
	M	*SD*	*M*	*SD*
All				
Negative	13.14	2.77	10.48	2.29
Neutral	9.59	2.07	8.82	4.02
Positive	10.32	1.80	10.17	1.95
Early				
Negative	16.46	10.11	13.19	10.97
Neutral	11.91	7.93	13.66	11.46
Positive	12.08	8.55	12.48	9.45
Middle				
Negative	12.75	7.35	9.65	10.10
Neutral	9.25	6.23	8.25	9.45
Positive	9.95	8.19	9.37	8.26
Late				
Negative	10.20	6.78	8.55	10.22
Neutral	7.59	6.54	4.49	9.43
Positive	8.87	8.51	8.73	9.08

(b) Central	*M*	*SD*
All		
Negative	−0.44	4.64
Neutral	−2.43	3.24
Positive	0.43	3.93
Early		
Negative	−5.47	9.23
Neutral	−6.33	7.72
Positive	−4.02	6.03
Middle		
Negative	0.50	8.56
Neutral	−1.28	6.82
Positive	1.60	6.91
Late		
Negative	3.70	8.96
Neutral	0.36	6.66
Positive	3.73	6.28

(c) Frontal	*M*	*SD*
All		
Negative	−4.89	5.37
Neutral	−6.42	3.92
Positive	−3.36	4.27
Early		
Negative	−11.02	9.13
Neutral	−10.89	8.71
Positive	−8.42	6.39
Middle		
Negative	−3.64	9.55
Neutral	−5.21	9.19
Positive	−2.06	8.17
Late		
Negative	0.02	9.43
Neutral	−3.15	8.45
Positive	0.49	7.58

early window, illustrated in Fig. 2E [early: $r(35) = .40$, $p = .02$; middle: $r(35) = .34$, $p = .03$; late: $r(35) = .12$, $p = .48$]. This indicated that larger emotional LPP responses were related to decreased heart rate variability. Heart rate and subjective ratings of emotion were not significantly correlated with the LPP in this cluster.

Within the central cluster, the response to positive images in the early, middle, and late LPP windows correlated positively with subjective arousal [early: $r(29) = .48$, $p = .008$, middle: $r(29) = .47$, $p = .01$; late: $r(29) = .38$, $p = .05$]. The response to negative images in the middle LPP window correlated negatively with subjective valence, $r(29) = -.45$, $p = .01$. Physiological responses were not correlated with the LPP in this cluster.

Within the frontal cluster, the response to positive images in the early and late LPP windows correlated positively with subjective arousal ratings [early: $r(29) = .43$, $p = .02$; late: $r(29) = .37$, $p = .05$]. The response to negative images in the middle and late LPP windows correlated negatively with subjective valence [middle: $r(29) = -.47$, $p = .01$; late: $r(29) = -.39$, $p = .03$]. Physiological responses were not correlated with the LPP in this cluster.

3.1.5. Summary of emotion responses

Children's subjective and psychophysiological responses indicated that the positive and negative images elicited greater emotion responses than the neutral images. In the negative emotion condition, children showed more coherence in subjective and psychophysiological responses than in the positive emotion condition. That is, for negative scenes, children showed increased psychophysiological arousal in parallel with subjective ratings of increased arousal and decreased valence. In contrast, for positive scenes, children rated the scenes as subjectively arousing, but showed no significant increase in psychophysiological arousal. Similarly, the amplitude of the LPP in ERP covaried with both subjective and psychophysiological responses to negative scenes, and covaried with subjective but not psychophysiological responses to positive scenes.

Notably, significant age-related differences in the emotional LPP were observed in the posterior cluster, where older children showed strong emotion responses across windows to negative stimuli specifically, and younger children showed relatively late emotion responses that were not strongly differentiated by condition. Across groups, emotion responses emerged at the central and frontal clusters whereby responses were larger to positive versus neutral stimuli.

3.2. Recognition memory

3.2.1. Behavioral recognition

Following prior research by Dolcos et al. (2005) and Weymar et al. (2011), we used corrected recognition scores to examine children's recognition memory. Scores were calculated by subtracting the proportion of false alarms from the proportion of hits within each emotion condition for each participant (proportion scores for false alarms and hits were relative to the total number of new and old trials presented, respectively). Confidence ratings were not included because they were not available for younger children and there was low variability in ratings among older

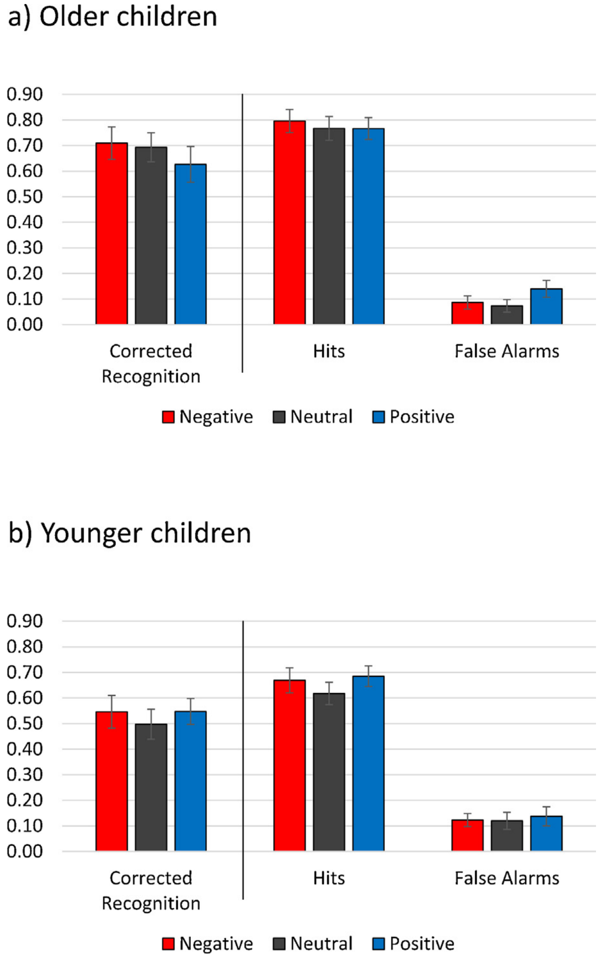

Fig. 3. Corrected recognition scores, including component scores of hits and false alarm proportions, plotted by emotion condition, for (a) older and)b) younger children. Corrected recognition calculated as the proportion of hits minus the proportion of false alarms. Error bars represent ± 1 *SEM*.

children.[4] Two-way mixed ANOVAs were calculated on the corrected recognition scores to examine children's recognition memory performance as a factor of age and emotion. Descriptive statistics are plotted in Fig. 3, separate for older and younger children in Panels a and b, respectively.

Overall recognition performance was strong, with significantly higher performance than chance, $t(34) = 14.36$, $p < .001$. An age effect that approached statistical significance was observed, $F(1,33) = 3.26$, $p = .080$, $p\eta^2 = .090$, with stronger performance by older versus younger children (both groups performed above chance). Effects of emotion did not reach statistical significance.

3.2.2. ERP recognition

To examine recognition memory effects in children's ERPs we calculated a 2 (Item: old, new) × 3 (Emotion: positive, neutral, negative) × 2 (Age: younger, older) mixed ANOVA for mean amplitude in each of the three clusters (posterior, central, and frontal) in each of the three windows (early, middle, late).

3.2.2.1. Posterior cluster. Waveforms are plotted in Fig. 4, Panels a and b, for older and younger children, respectively. In the early window, the interaction of memory, emotion, and age was significant, $F(2,62) = 4.30$, $p = .018$, $p\eta^2 = .122$. Follow-up analysis by age group revealed a significant interaction of memory and emotion in older children, $F(2,28) = 4.43$, $p = .021$, $p\eta^2 = .240$. Further investigation revealed that the interaction was driven by item effects in the negative condition, $t(14) = 4.13$, $p = .001$, with larger responses to old versus new negative images (old: $M = 16.11$ μV, $SD = 8.11$; new: $M = 7.62$ μV, $SD = 10.14$). Memory effects were not observed in the other emotion conditions. No memory effects were observed in the younger group.

No memory effects were observed in the middle and late windows.

3.2.2.2. Central cluster. There were no statistically significant effects of memory in the early and middle windows. In the late window, a main effect of memory was observed, $F(1,31) = 6.16$, $p = .019$, $p\eta^2 = .166$, with larger responses to old versus new images (old: $M = 5.63$ μV, $SD = 7.84$; new: $M = 3.49$ μV, $SD = 6.03$).

3.2.2.3. Frontal cluster. No memory effects were observed in any window.

3.2.3. Summary of recognition memory effects

Overall, children remembered the images, with stronger performance by older versus younger children. In their behavioral responses, older children showed an emotion effect on memory (better memory for negative vs. positive images), whereas younger children did not.

In ERP responses, evidence for an emotion effect on memory came in the early window of the posterior cluster, for older children only. Specifically, there was a significant recognition effect within the negative condition only. The only other memory effect that emerged was observed across conditions in the late window of the central cluster.

4. Discussion

We examined school-age children's processing of and subsequent memory for emotional stimuli. First, we evaluated children's experience of the emotional stimuli. Children rated the stimuli as emotional, with no differences between age groups, and the ratings were similar to those of adults in other studies. Further, across the sampled ages (5–8 years), children showed emotion effects in their physiological and ERP responses. At posterior sites, where emotion effects are largest (Hajcak et al., 2012), the emotion effects were more robust for older than younger children (effects were sustained from 800 to 2000 ms, and only emerged late in the window, from 1600 to 2000 ms in younger children). The amplitude of ERP emotion effects

[4] Among children who provided confidence ratings, >90% of ratings were a 'very sure' response.

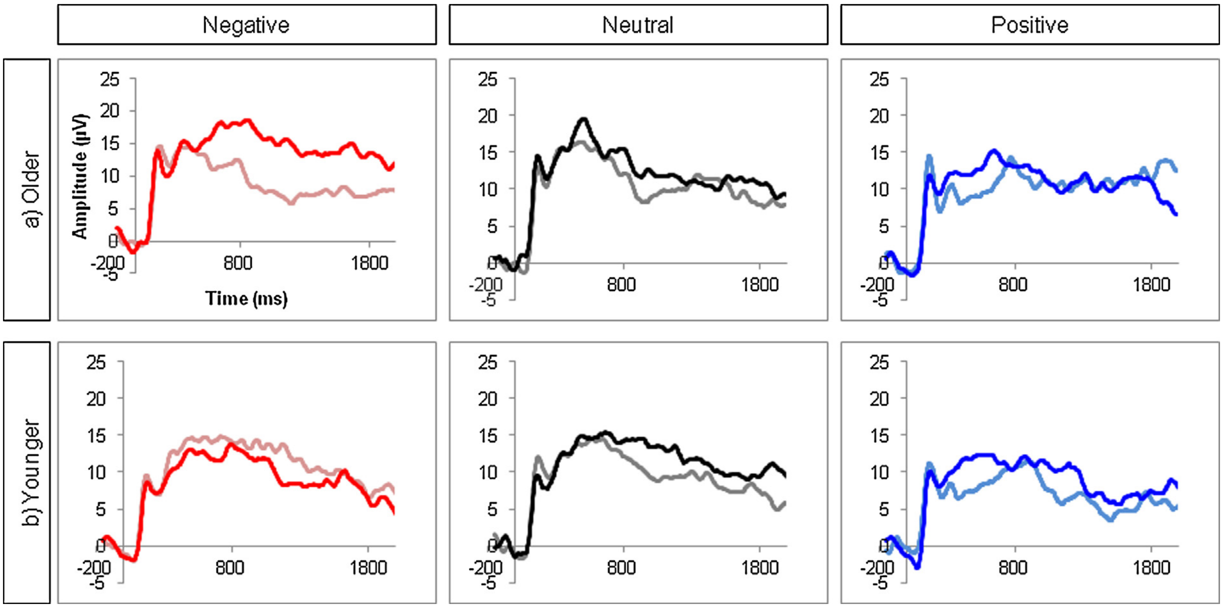

Fig. 4. Grand averaged waveforms at the posterior cluster by emotion condition at recognition from older and younger participants, panels a and b, respectively (negative in red, neutral in black, and positive is plotted in blue; 'old' is in darker shades, 'new' in lighter shades). A smoothing algorithm was applied to ERP plots; raw data was used in all ERP analyses. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of the article.)

was related to children's subjective and psychophysiological responses. Interestingly, age-related differences were observed in the onset of ERP effects, such that older children showed an earlier response to negative stimuli than younger children. This suggests that the neural processing of negative emotion becomes faster during the school-age years. Because the effect was observed only for the negative condition, it cannot be due to general increases in speed of processing. Thus we did not observe greater emotional reactivity in younger relative to older children, as predicted, and we found evidence for selective processing of negative emotion with age. The current findings enhance our understanding of emotional processing in school-aged children, with suggestive evidence that emotional development continues in the school years.

Children also demonstrated successful recognition memory in their ERP and behavioral responses. Although emotion did not influence behavioral recognition performance, emotion enhanced the size of ERP recognition effects in the older group. Specifically, ERP recognition effects specific to the negative condition were observed at posterior sites in older but not younger children (among general memory effects across conditions). Thus there were age-related increases in the enhancing effect of emotion on recognition memory, with children under age 7.5 showing no emotion effects on memory, and children older than 7.5 beginning to show adult-like patterns of emotional memory. This is the first neuroimaging study to examine early development in the enhancing effect of emotion on memory.

4.1. Emotional development in school-age children

Children's emotion processing has been examined in a variety of contexts, using a range of measures including visual attention, behavior, ratings, and neural and physiological responses. For example, 4-month-olds, in their looking behavior, can distinguish different emotions in facial expressions (e.g., LaBarbera et al., 1976), and preschoolers can sort and identify facial expressions depicting specific emotion categories (e.g., Widen and Russell, 2008), as well as correctly label specific emotion categories for emotion-inducing stories (e.g., Camras and Allison, 1985). Further, in behavioral and electrophysiological investigations, even 12-month-olds modify their behavior and attention based on emotional signals, demonstrating the functional significance of emotion information (e.g., Leventon and Bauer, 2013). Here, we found that children as young as 5 years rate positive and negative stimuli as emotional, and show increased electrophysiological (ERP) and physiological responses to these stimuli, similarly to adults. As has been observed in adults (Cuthbert et al., 2000), the amplitude of the ERP response to emotional stimuli covaried with individual differences in subjective and physiological emotional responses.

Interestingly, there was greater coherence in our three measures of emotion response to negative than to positive stimuli. In healthy adults, the emotional LPP has been linked primarily to emotional arousal responses, but here, the LPP in school-age children diverged from physiological responses to positive stimuli. It is possible that the current measures of physiological arousal failed to index the full range of reactions that children may have experienced. In future research, it will be important to assess aspects of psychophysiology mediated by the sympathetic nervous system, such as pupil dilation or skin conductance responses. The finding not only highlights the value of including multiple measures to collect a more complete assessment of the emotion response, but also prompts the need for further research on emotion to include both negative and positive valence to evaluate potential differences in the processing and development of the response to emotional stimuli of different valences.

Notably, the emotion effects in ERP responses became more robust in children older than 7.5. Although much of the development in emotional systems takes place very early in life, this finding provides novel evidence that the school years are also a period of developmental change. The ERP effects may be indicative of a different functional experience of emotion between the two age groups. The pattern of emotion effects in the posterior LPP (where emotion effects are strongest, e.g. Hajcak et al., 2012), is consistent with Davidson's affective chronometry argument whereby different windows within the emotion response may represent different functional components of emotion processing (Davidson, 1998). Davidson identified four components of the emotion response that may be indicative of underlying emotion processes: threshold for reactivity, peak amplitude of response, rise time to peak, and recovery time. The differences observed in the present findings seem particular to the third element, rise time to peak, and suggest that emotion response systems are slower in younger versus older school-age children. In this period of development, children are still learning about the causes of emotion and how to change emotional experience (Denham, 1998), thus perhaps it is these maturing emotion systems that delays the onset of emotion effects in younger children.

4.2. Development of emotional memory

Investigations of children's memory for emotional events have largely examined personally experienced events (autobiographical memories), and often featuring stressful or unique experiences (e.g., a natural disaster, as in Ackil et al., 2003). Children as young as 3 years recall accurate details of such experiences, however it has yet to be formally examined how children remember everyday emotional events, and little evidence to indicate developmental trajectories for enhancing effects of emotion on subsequent memory. Compared to personal experiences, experimental stimuli that depict commonplace emotional events and vary on dimensions of valence and arousal offer an experimentally more controlled approach to examine encoding and retrieval of emotional experience.

Main effects of emotion on children's behavioral recognition responses were not apparent. This is interesting given converging evidence from subjective and physiological measures, indicating that the positive and negative stimuli were more arousing than the neutral stimuli, and differed in valence. This may suggest a developmental trend, such that the enhancing effect of emotion on memory has not yet emerged in the developmental period examined here (5–8 years of age), possibly due to immature connections in the emotion-memory network. However, several previous studies do provide evidence for emotion effects on memory in the school years (Cordon et al., 2013; Davidson et al., 2001). High levels of recognition performance might have limited our power to detect emotion effects. Yet even though younger children had lower performance, emotion effects on memory were not detected in this group either. Future studies might address this issue by increasing retrieval demand, increasing the delay between encoding and recognition, or including a recall task.

The data highlight the importance of using multiple methods to assess emotion and memory. We did not observe an emotion effect on behavioral indices of children's memory; however, the ERP data expand the picture of the underlying processes supporting recognition memory. In ERP responses, we observed an increased recognition effect for negative stimuli, which was only apparent in the older group of children. This suggests that the school years represent a time of developing emotion effects on retrieval, perhaps indicating that the neural and cognitive systems for emotion and memory are becoming more integrated during this period. The findings also raise the possibility that negative emotion influences memory earlier in development than positive emotion.

The enhancing effect of emotion on memory may take place at several stages of the memory process- encoding, consolidation, retrieval. Because physiological and ERP responses at the time of encoding are indicative of emotion effects, we argue that encoding processes are at least partially responsible for the enhancing effect of emotion on memory. Future research should be conducted to explore the contributions of encoding, consolidation, and retrieval during the development of emotional memory.

4.3. Limitations

Unfortunately we did not have the opportunity to examine encoding-related neural activity using the subsequent memory paradigm, due to the low incidence of 'miss' trials at recognition. Thus we could not observe how arousal may have influenced neural processes reflecting successful encoding among school-aged children. Future research should modify the tasks employed in the current research to increase the incidence of miss trials to permit examination of this question. Increased sampling of encoding, post-encoding, and retrieval processes could inform where in the life of a memory that the enhancing effects of emotion emerge, and where there might be developmental changes in emotional memory processes.

Subjective ratings of the emotional stimuli were made on a subset of the images and collected after retrieval, and thus not at the initial experience (encoding) of the stimuli. It is possible that ratings would differ between the two experiences. We do not view this as a limitation on interpretation, however, because the collected ratings were similar to those from previous investigations (e.g., McManis et al., 2001),.

4.4. Conclusions

The findings from the present study inform our understanding of children's memory for emotional stimuli, adding to the body of work on children's memory for personally experienced emotional events (e.g., enhanced ERP processing for positive relative to neutral autobiographical memories observed in 7–10-year-old children, Bauer et al., 2012). Specifically, the findings suggest age-related emergence of an emotion effect on school-age children's memory at 7–8 years of age. The findings are suggestive that in the early school-age years, emotional experience is less-well integrated with memory processes, whereby children demonstrate emotion effects that do not significantly affect memory processes. Further work should examine the behavioral and neurophysiological patterns of children's and adolescents' emotional memory to chart the developmental trajectory of the emotion effect.

Conflict of interest

My coauthors and I have followed APA ethical standards in all aspects of the work, and we do not have any interests that would be interpreted as influencing the research.

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