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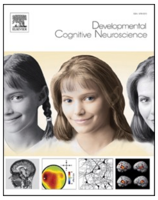

Neuroimaging of valence decisions in children and adults

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ABSTRACT

To date, the neural underpinnings of affective components in language processing in children remain largely unknown. To fill this gap, the present study examined behavioural and neural correlates of children and adults performing the same auditory valence decision task with an event-related fMRI paradigm. Based on previous findings in adults, activations in anterior and posterior cingulate cortex, orbitofrontal cortex and left inferior frontal gyrus were expected for both positive and negative valence categories. Recent behavioural findings on valence decisions showed similar ratings and reaction time patterns in children and adults. This finding was successfully replicated in the present study. On a neural level, our analysis of affective language processing showed activations in regions associated with both semantic (superior and middle temporal and frontal) and affective (anterior and posterior cingulate, orbitofrontal and inferior frontal, insula and amygdala) processing. Neural activations in children and adults were systematically different in explicit affective word processing. In particular, adults showed a more distributed semantic network activation while children recruited additional subcortical structures.

1. Introduction

Within the last decades, many behavioural and neurocognitive studies focused on the interplay of affect and semantics using various stimuli, like single words (e.g., Aryani et al., 2018, 2019; Dreyer and Pulvermüller, 2018; Jacobs et al., 2015; Kuchinke et al., 2005; Maddock et al., 2003; Vigliocco et al., 2013), word compounds (Kuhlmann et al., 2016, 2017) or literary texts (e.g., Hsu et al., 2014, 2015a,b,c,; Jacobs, 2015; O'Sullivan et al., 2015; Lehne et al., 2015). While neural correlates of affective semantics are widely studied in adults (e.g., Citron, 2012), there is a dearth of empirical findings in children with only few studies focusing on clinical cohorts, e.g., children with autism spectrum disorder (e.g., Lartseva et al., 2015). Besides this clinical perspective, research on language processing in children mostly concentrates on cognitive developmental aspects (e.g., Liebig et al., 2017; Weiss-Croft and Baldeweg, 2015; Youssofzadeh et al., 2018) disregarding the ubiquitous affective component of language. Interestingly, careful reading of studies on language processing in children also reveals some affective contributions. For example, Moore et al. (2010) investigated semantic processing in seven to ten year old children and adults finding similar activations e.g. in temporal and frontal regions. Additionally, however, activation in the right amygdala, insula, and bilateral thalamus were reported for children as well as activation in the right insula and left thalamus for adults. Such findings suggest that affective components are tightly intertwined with lexical semantics (Vigliocco et al., 2013), and that affective semantic processing is very similar in children and adults.

Regarding processing similarities in children and adults, the results of a behavioural study by Sylvester et al. (2016) in which children rated valence, arousal, and imageability of written and spoken single words showed that children's ratings could be predicted by those of young adults. In particular, children showed the two ubiquitous phenomena observed in adults in response to emotional word material: the asymmetric U-shaped function relating valence to arousal ratings and the inversely U-shaped function relating response times to valence decision latencies. Furthermore, the reaction time patterns of both children and adults showed a positivity superiority effect (positive words were rated fastest; Lüdtke and Jacobs, 2015) in both the visual and auditory modality. However, generally longer response latencies for children were visible across tasks and stimuli categories, which might be due to a less developed mental lexicon, less top-down control (Moore et al., 2010) and/or less automatic language processing (Weiss-Croft and Baldeweg, 2015). Concerning processing of emotional stimuli more generally, LoBue et al. (2018) recently reported strong similarities in children and adults when asked to evaluate facial emotional expressions. On a neural

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level, notable similarities between children and adults were reported at least for semantic processing (see review by Weiss-Croft and Baldeweg, 2015). Altogether, these studies indicate highly similar affective processing in adults and children across different types of stimuli. The neural underpinnings of affective lexico-semantic processing in children, however, have so far escaped detailed investigation.

1.1. *Neural correlates of word valence processing*

Valence is often investigated in relation to arousal systematically yielding nonlinear interactions (e.g., Sylvester et al., 2016). In the present neuroimaging study we chose to control our word stimuli for arousal to avoid such complex interactions (see Citron, 2012, or Jacobs et al., 2015, for review). In her comprehensive review, Citron (2012) identified the following core regions for valence processing: orbitofrontal cortex (OFC), anterior cingulate cortex (ACC), posterior cingulate cortex (PCC), caudate and subgenual cingulate cortex. Activation in striatum and OFC was more likely associated with positive valence, while negatively valenced stimuli most often activated amygdala and insula. However, all results summarized in this review were restricted to certain regions of interest. When instead whole brain results are scanned for association with affective processing, regions beyond these well-established areas emerge. In particular, several regions usually associated with the semantic system become visible (Price, 2010, 2012). For example, Maddock et al. (2003) found activations in left (superior and middle) temporal and left (inferior, middle and superior) frontal regions additionally to valence specific activation in PCC during a valence decision task (VDT).

1.2. *The affective semantics perspective on valence*

How do humans decide whether an object, word or person is positive or not? A theory-guided and empirically well supported hypothesis assumes that valence is a semantic ‘super-feature’ (Jacobs et al., 2016) that – in the case of verbal stimuli – results from a yet unknown integration of both experiential (i.e., embodied) and distributional (i.e., associative) information (Vigliocco et al., 2009). This hypothesis of a lexico-semantic foundation of valence is based on the general hierarchical emotion theory by Panksepp (1998, 2008). Corroborating evidence was obtained by Briesemeister and colleagues in a study where adults performed an *implicit* lexical decision task using both electroencephalography (EEG) and functional magnetic-resonance-imaging (fMRI) (Briesemeister et al., 2014; Briesemeister et al., 2015). The theory posits that valence is a higher cognitive component of emotion located at the tertiary process level that recruits neocortical areas such as inferior frontal or orbitofrontal gyri. Processing in these areas is supported by structures associated with the secondary process level in the limbic system, such as the right-hemispheric amygdala. Computational studies showed that the valence of words can be predicted by their association to a selected set of ‘emotion labels’ taken from extant emotion theories (Westbury et al., 2015; see also Jacobs, 2017, 2019; Jacobs and Kinder, 2018). First neurocomputational evidence for the hypothesis indicated a significant correlation in the lIFG between positive valence of words and the number of semantic associates (Hofmann and Jacobs, 2014). Supporting neurocognitive evidence for the idea of a valence representation based on associations in cortical lexico-semantic networks came from a study using the VDT suggesting that word valence is partially derived from distributional information (Kuhlmann et al., 2017). Computational evidence furthermore suggests that the exploitation of affective activations facilitates the acquisition of lexical semantics in children (Kolovou et al., 2017).

1.3. *Present study*

The present study examined and compared explicit affective word processing in adults (19–30 years) and children (6–9 years) using a VDT in which positive, negative, and neutral words (controlled for arousal) were presented auditorily in the fMRI scanner. Following the affective semantics perspective outlined above, it was hypothesised that valence decisions elicit activation in regions associated with both semantic and affective processing in children and adults. In particular, activation associated with semantic processing was expected in left superior and middle temporal, and frontal gyrus (e.g., Binder et al., 2009; Price, 2012; Weiss-Croft and Baldeweg, 2015) as well as lIFG, ACC, PCC, OFC, insula, amygdala, caudate, striatum, and subgenual cingulate cortex (Citron, 2012; Kuhlmann et al., 2017).

By the age of six, children have acquired most important structures for language comprehension and expression (e.g., Lidzba et al., 2011). Due to lifelong growth of the mental lexicon, the semantic network changes across age (e.g., Brysbaert et al., 2016; Verhaeghen, 2003) and has notably fewer associates in children than in adults (De La Haye, 2003; Denhière et al., 2007; Dubossarsky et al., 2017; Stella et al., 2017). Given these differences in the size and density of the mental lexicon, it was further predicted that children either show less distributed or smaller cluster activations compared to adults. To test both hypotheses, first semantic processing was analysed independently of valence, followed by differential analyses of positive and negative words on the behavioural (reaction times) and the neural level for both age cohorts. In a last step, valence processing of children and adults was directly compared to examine similarities and differences across age.

2. Material and methods

2.1. *Participants*

Informed written consent was obtained from the legal guardian of the children and the adult cohort. The adults were told that they participate in a study for children as a reference cohort. Twenty-four children were invited to the experiment. The children were recruited from the control group of a large study on dyslexia (Liebig). Seven children were excluded because of strong movement artefacts (see section 2.4). In regard to data balance, fMRI data of 17 adults was analysed as reference cohort. Thus, the data of 17 native German-speaking children (7 females; 6–9 years; $M = 7.65$; $SD = 0.86$) and 17 adults (10 females; 19–30 years; $M = 24.0$ years, $SD = 3.97$) entered the analysis. The cohort of children also took part in a separate study where they had already received scanner training and thus were familiar with the setup. The training included a session in a mock scanner to familiarize children with the noise and environment. The children were told that the scanner is a rocket flying to the moon and the head coil is the astronaut’s helmet. The whole scanning procedure was embedded in a narrative describing a flight to the moon and back. The children trained pressing the alarm button, talking to the operator during scan breaks and to remain motionless during the scanner session. Only those children took part in the actual experiment that felt comfortable in the mock scanner. The adults were psychology students participating for student credit. All participants had no history of neurological diseases. The Ethics Committee of the German Association for Psychology approved experimental procedures.

2.2. *Stimuli*

60 words (49 nouns, 11 verbs) were used from the kidBAWL (Sylvester et al., 2016), a validation for children of an adults’ word database including valence, arousal, and imageability ratings from 6 to 12 years old children to ensure the children’s familiarity with the words e.g., ‘holidays’ (positive), ‘beast’ (negative), and ‘battery’ (neutral). Twenty words were selected for each valence category (neutral, negative, positive, see supplementary material) matched for arousal, number of letters, and syllables. Word frequencies were taken from the *childLex* database (Schroeder et al., 2015) to ensure similar distributions over all three valence categories. For further details see Table 1 including

Table 1
Semantic and lexical variables of presented word stimuli.

Valence category	Positive		Negative		Neutral		
Word property	*M*	*SD*	*M*	*SD*	*M*	*SD*	*p*
Valence	0.87	0.39	−1.35	0.47	0.28	0.31	<0.001*
Arousal	0.22	1.03	0.39	0.71	−0.14	0.75	0.137
Letters	6.1	1.44	6.0	1.17	6.0	1.17	0.959
Syllables	1.9	0.44	1.8	0.52	1.95	0.51	0.623
Frequency per million	142.04	428.99	36.39	115.27	33.47	51.31	0.326

Note. valence ratings z-transformed (scale −2.5 to 2.5) range for positive (r = 0.5–2.5), negative (−0.5 to −2.5) and neutral words (−0.5 to 0.5). Arousal ratings z-transformed (scale −2.5 to −2.5).

relevant word features. The word valence which is based on former children's ratings (Sylvester et al., 2016) was used for the data analyses. Words were presented auditorily to avoid potential effects of reading ability. Sylvester et al. (2016) showed that visual and auditory word presentation lead to equivalent behavioural results in valence ratings (see also Chee et al., 1999). Stimuli were spoken by a female computer voice (MAC OSX voice "Anna"). Each spoken word stimulus lasted 1 s.

2.3. *Experimental paradigm*

Participants performed a forced valence decision task (VDT) while in the fMRI scanner. In each of the two runs the VDT was performed for 2.75 min and 30 word stimuli (10 stimuli per valence category) were presented in an event-related design paradigm. In this task, participants were instructed to decide – as fast and accurate as possible – whether a presented word has a positive or negative meaning and indicated their answer via index finger button press. After 1 s stimulus presentation, participants had 2 s for their response, during which pictures of a sad and happy smiley were displayed as response options. Response hand (left vs. right) was balanced over runs to control for motor confounds in the fMRI data. Words were presented in pseudorandomised order where the presentation algorithm controlled that not more than two words of the same valence category were presented consecutively. Inter trial intervals were optimised using Optseq2 algorithm (Dale, 1999) to $M =$ 1000 ms, $SD =$ 599 ms, $r =$ 500−4500 ms. The VDT was designed as an active task with responses by the participants to ensure attention to the stimuli and processing of affective semantic aspects. The task turned out to be quite effortful for the children. Reaction times were collected and analysed to replicate previous behavioural findings (Sylvester et al., 2016). For the analysis of neural activity, the predefined valence categories based on Sylvester et al. (2016) were used. During the scanner session, participants performed additional runs of a lexical decision task, which is not object of the present study.

2.4. *fMRI data acquisition and analyses*

The functional data was recorded with a 3 T SIEMENS Tim Trio scanner (SIEMENS Erlangen, Germany) at the Centre for Cognitive Neuroscience Berlin (CCNB). High resolution T1 weighted anatomic reference images were collected as a set of 176 sagittal slices (slice thickness = 1 × 1 × 1 mm, TR = 1.9 s, TE = 2.52 ms, FOV = 256 mm). In both runs 66 functional images were acquired each with a multi echo planar sequence (voxel size = 3 × 3 × 3 mm^3, TR = 2330 ms, TE1 = 15 ms, TE2 = 34 ms, TE3 = 53 ms, FOV = 192 mm, FA = 70°). In total, the scan procedure took about 24 min. Exact scanner time depended on the individual need for breaks between the runs. The auditory stimuli were presented via circumaural earphones (VisuaStim, MR Research, USA). The response pictures were presented in the middle of the screen with a white background on dual display goggles (VisuaStim, MR Research, USA) using Python 2.7 (Python Software Foundation).

fMRI data analysis was performed using SPM12 (Wellcome Department of Imaging Neuroscience, University College London, UK, 2014). To correct for motion, images were realigned to the first image. Next, the ArtRepair toolbox (Mazaika et al., 2007) was used to determine images with scan-to-scan motion parameters over 1.5 mm/TR over global mean (Karipidis et al., 2017). Participants moving more than nine volumes in a row were excluded. Thus, there were never more than eight consecutive volumes interpolated from preceding and following images. In total, less than 1.2 % of scans were repaired in this manner. For the children, an age-appropriate segmentation template for six-year-old children based on Template-O-Matic toolbox (Wilke et al., 2008) was generated and used for a precise segmentation of children's T1 images. Adults' and children's T1 images were segmented into six tissue probability maps (white, grey, CSF, bone, soft tissue, and air). In a next step, the DARTEL algorithm (Ashburner, 2007) was used to generate a group mean template separately for children and adults, which enhances comparability within each group in the normalisation preprocessing. Consecutively, the functional images were spatially normalised to MNI space and smoothed with an isotropic 8 mm full-width-at-half-maximum (FWHM) Gaussian kernel. Studies supported the feasibility of using adult-defined stereotaxis space for analysis of children older than six years (Kang et al., 2003). Finally, data was detrended to remove global drifts (Macey et al., 2004).

For statistical assessment of activation differences, a standard general linear model approach was used as implemented in SPM. As regressors the trials in three conditions according to their valence category positive, negative or neutral were modelled. The realignment parameters were included as regressors of no interest. On the first level model baseline contrasts of the positive, negative, and neutral word conditions and the contrasts positive > neutral and negative > neutral were computed. Group level differences were assessed in second-level ANOVA designs using the flexible factorial design specification of SPM. First commonalities were tested between positive, negative, and neutral word processing as the conjunction against the conjunction null hypothesis (Friston et al., 2005). Next, another second-level design was computed to test group level effects of the contrasts positive > neutral and negative > neutral for adults and children respectively. All results are presented $p < 0.05$ familywise error corrected (FWE) on the cluster level.

On the behavioural level, reaction times were analysed by calculating the mean times between stimulus presentation and button press using a one factorial ANOVA and pairwise comparisons between valence categories by t-tests.

3. Results

3.1. *Semantic processing independently from valence*

A conjunction analysis over all three valence categories was computed separately for adults and children. For both age cohorts, activations were found in bilateral superior, left middle temporal, and right middle frontal gyrus (see Tables 2 & 3 , Figure Fig. 1A), showing the expected activation associated with auditory semantic processing (e.g., Price, 2012; Weiss-Croft and Baldeweg, 2015). Both age cohorts also showed activation in bilateral thalamus and calcarine sulcus. Children additionally showed activation in bilateral insula, right precentral gyrus,

Table 2
Conjunction analysis for adults' neural activity for positive, negative and neutral words.

Anatomical location	MNI			Size	Peak
	x	y	z	k	T
Frontal					
R Middle frontal	38	44	24	6938	10.39
L Supplementary motor area	12	12	52		9.93
R Middle cingulate gyrus	6	22	36		9.22
Subcortical structures					
R Thalamus	16	−10	10	995	7.67
L Thalamus	−8	−12	10	139	7.62
Temporal					
L Superior temporal gyrus	−60	−12	0	4036	10.84
L Middle temporal gyrus	−60	−24	−2		10.52
R Superior temporal gyrus	56	−32	4	4918	13.49
Occipital					
L Calcarine	−10	−80	4	331	9.02
R Calcarine	14	−82	6	241	7.7
R Lingual	16	−68	−2		3.65

Note. Clusters are presented $p < 0.05$ FWE corrected on the cluster level.

Table 3
Conjunction analysis for children's neural activity for positive, negative and neutral words.

Anatomical location	MNI			Size	Peak
	x	y	z	k	T
Frontal					
R Precentral	46	−18	56	935	7.0
R Middle frontal gyrus	32	38	22	284	7.05
Subcortical structures					
L Insula	−34	18	4	1714	10.24
L Pars orbitalis	−46	16	−4		8.86
L Pars triangularis					7.33
L Thalamus	−8	−22	−8	935	9.35
R Thalamus	10	−12	−6		8.18
R Putamen	28	24	2	625	7.24
R Insula	32	18	12		6.62
R Middle cingulate gyrus	8	20	38	5143	9.93
L Supplementary motor cortex	−4	14	44		9.65
L ACC	−10	26	26		8.53
Temporal					
L Middle temporal gyrus	−58	−46	10	3314	11.95
L Superior temporal gyrus	−62	−24	6		10.93
R Superior temporal gyrus	58	−20	2	2393	12.12
Occipital					
L Calcarine	−10	−84	8	2223	9.5
R Calcarine	16	−80	10		8.26
L Lingual gyrus	−10	−70	−4		6.98

Note. Clusters are presented $p < 0.05$ FWE corrected on the cluster level.

middle cingulate cortex, and putamen (Fig. 1C).

3.2. Affective semantic processing in adults

In adults, a significant difference in reaction times was found according to valence *(F(2,998) = 119.74,* $R^2 = 0.19$*)* with shortest reaction times for positive words *(M = 514 ms, SD = 22 ms)*, followed by negative words *(M = 553 ms, SD = 22 ms)* and neutral words (M = 955 ms, SD = 22 ms), but without a significant difference between positive and negative words.

To test for activation related to the affective semantic components of word processing, contrasts of positive and negative words against neutral words were computed. In line with the hypothesis, positive words showed stronger activation in right striatum (caudate and putamen) and ACC as well as left insula than the neutral words. Regarding semantic activation, left superior frontal and middle temporal gyrus activation was found. Additionally, activation clusters were found in frontal (precentral gyrus) and occipital (left inferior gyrus and right calcarine) areas (Table 4, Fig. 1B), as well as in supplementary motor area (SMA).

For negative words stronger activation was found in lIFG and right PCC compared to neutral words. Similar to positive words, bilateral SMA and precentral activation was also revealed by the negative > neutral contrast (Table 5, Fig. 1B). To formally test for common activation clusters in the positive > neutral and negative > neutral contrasts, a conjunction analysis of both was computed. This analysis did not reveal any significant clusters on $p < 0.05$ FWE.

3.3. Affective semantic processing in children

Behaviourally, the same order of reaction times regarding valence categories was found for children *(F(2,792) = 19.05,* positive words: *M = 770 ms, SD = 25 ms*; negative words: *M = 869 ms, SD = 25 ms,* and neutral words: *M = 993 ms, SD = 25 ms*). All valence categories showed significant different reaction times. These results replicate those of Sylvester et al. (2016) who found the same order of response time means.

To examine neural affective processing the second-level contrasts positive > neutral and negative > neutral were computed. For positive words activation was found in frontal and subcortical regions. In line with the hypothesis, activation in left superior frontal gyrus might be associated with the expected semantic processing. Activation was also found in lIFG, as hypothesised for affective semantic integration. For affective processing, left ACC, and insula as well as right PCC activation was found. Besides these hypothesised regions, right inferior frontal, left thalamus, and hippocampus showed activation (Table 6, Fig. 1C).

For negative words stronger activation was found regarding the hypothesis in right amygdala and left hemisphere in OFC extending to lIFG accompanied by activations in ACC (Table 7, Fig. 1C). Additional activation was shown in lingual and middle occipital including angular gyrus. In contrast to the adults' results, the children's conjunction analysis for the contrasts positive > neutral and negative > neutral words showed significant activation in lIFG extending to the middle OFC, and activation in the left ACC (Table 8).

3.4. Valence effects comparing adults and children

To formally test for differences between adults and children the differential contrasts for positive > neutral and negative > neutral words were computed. Unexpectedly, stronger activation was found for adults compared to children only in regions associated with semantic but not with affective processing for positive > neutral words. These regions encompassed right superior temporal *(k = 204, z = 5.14, [56,−6, −6])*, parietal *(k = 765, z = 5.53, [18, −46, 68])*, left middle temporal *(k = 228, z = 5.13, [-54, -58, 4])*, lingual *(k = 221, z = 4.66, [−14, −80, −10])*, and fusiform *(k = 141, z = 4.64, [−42, −46, −20])* as well as postcentral (*k = 134, z = 4.59, [−34, −30, 40]*), middle occipital *(k = 134, z = 4.38, [−44, −74, 14])*, and right occipital pole (*k = 252, z = 4.22, [20, −92, 12]*) on *k = 134* FWE cluster corrected on $p < 0.05$.

The same pattern was revealed for the contrast negative > neutral words. Meaning that adults showed stronger activation than children in areas related to semantic but not affective processing. These encompassed bilateral middle temporal (left: *k = 252, z = 5.26, [−48, −32, 2]*, right: *k = 744, z = 5.67, [68, −34, 0])*, right middle frontal *(k = 136, z = 5.06, [28, 50, 18)]*, precuneus *(k = 487, z = 5.42, [6, −46, 66])*, and postcentral *(k = 542, z = 4.99, [42, −24, 46])*. In the left hemisphere, supramarginal *(k = 422, z = 5.18, [−44, −38, 34])* and SMA *(k = 493, z = 5.02, [−2, 8, 60])* activations reached significance on *k = 136* FWE cluster corrected on $p < 0.05$.

For positive > neutral words for children compared to adults, activations were found associated with both, semantic and affective processing. Regarding semantic processing, activation was shown in right superior parietal including angular gyrus *(k = 247, z = 5.2, [30, -76, 50])* and middle cingulum including ACC *(k = 180, z = 4.11, [2, 28, 30])*. In association with affective combined with semantic processing,

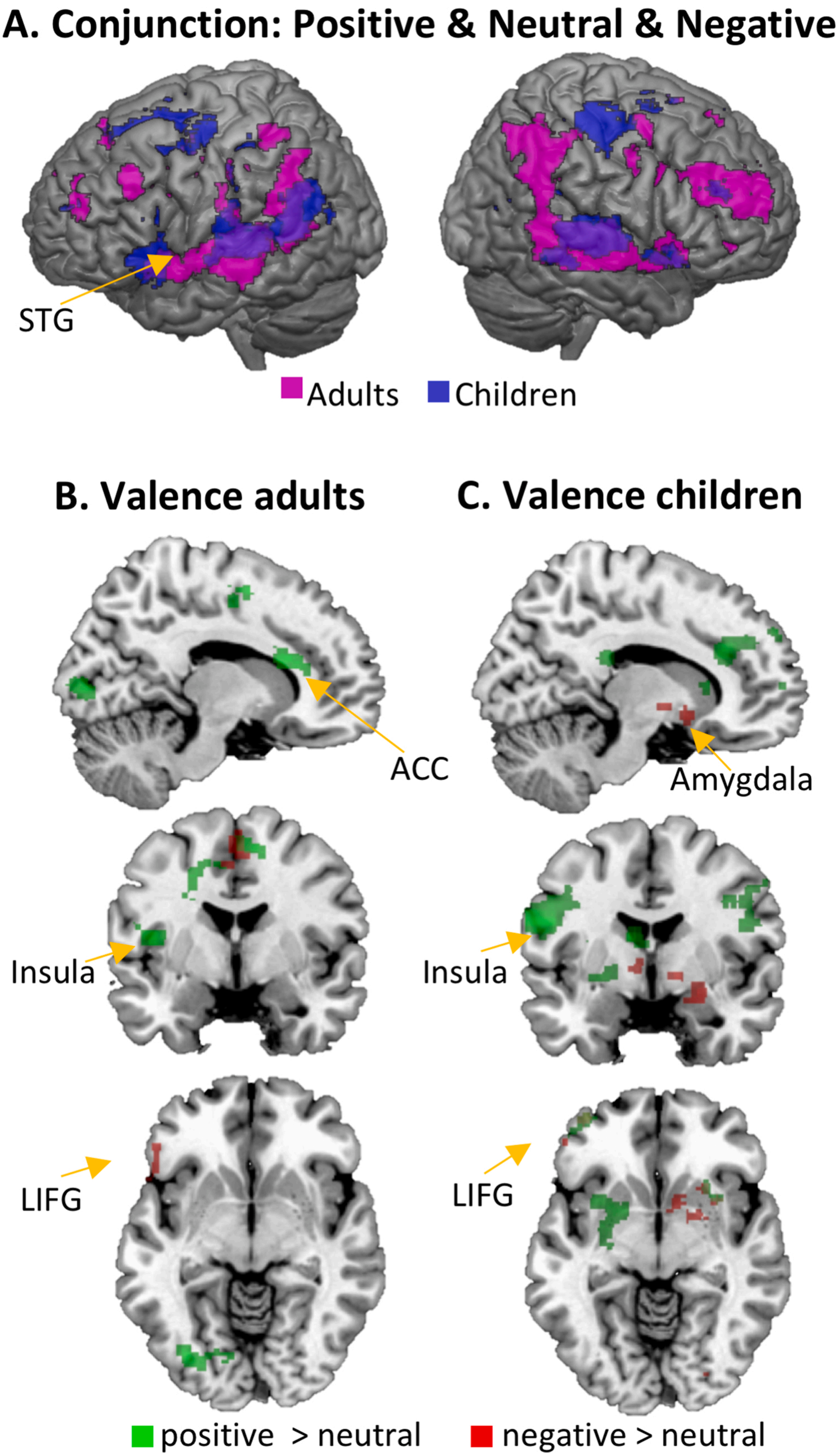

Fig. 1. Figure A. The language system of adults (pink) and children (blue) on a rendered brain surface showing the conjunction of neutral, positive and negative words. B. Valence activation in adults for positive > neutral words (green) and negative > neutral words (red). C. Valence activation in children for positive > neutral words (green) and negative > neutral words (red). All results are presented p<0.05 FWE corrected on the cluster level.

Table 4
Adults' neural activity associated with positive > neutral words.

Anatomical location	MNI x	y	z	Size k	Peak T
Frontal					
R Precentral	32	−20	42	150	5.46
R Postcentral gyrus	42	−28	48		4.17
Subcortical structures					
L Putamen	−22	8	14	172	6.06
L Caudate	−18	18	12		5.45
L Insula	−42	−2	10	145	5.41
L Rolandic operculum	−36	−6	−16		4.14
L Precentral gyrus	−52	−2	18		3.65
L Middle Cingulum	−20	6	34	189	5.08
L Superior frontal gyrus	−22	−2	42		4.54
R Caudate	14	20	18	304	6.59
R Anterior cingulum	20	34	14		4.04
Supplementary motor area					
R Supplementary motor area	8	0	56	189	5.44
L Supplementary motor area	0	−8	64		4.58
Temporal					
L Middle temporal gyrus	−36	−68	12	238	4.77
L Middle occipital gyrus	−50	−76	12		4.69
Occipital					
L Inferior occipital gyrus	−34	−76	−6	174	5.67
L Lingual gyrus	−12	−76	−4		4.23
R Calcarine	12	−88	4	203	5.27
R Superior occipital gyrus	24	−84	2		4.10
R Fusiform gyrus	28	−76	−2		3.89

Note. Clusters are presented $p < 0.05$ FWE corrected on the cluster level.

Table 5
Adults' neural activity associated with negative > neutral words.

Anatomical location	MNI x	y	z	Size k	Peak T
Frontal					
L Pars triangularis	−58	20	22	308	5.14
R Precentral	40	−22	54	273	4.91
Parietal					
R Angular gyrus	32	−46	28	152	5.80
R Posterior cingulum	22	−50	36		4.92
Supplementary motor area					
L Supplementary motor area	−2	8	58	543	5.94
R Supplementary motor area	2	0	56		5.29

Note. Clusters are presented $p < 0.05$ FWE corrected on the cluster level.

Table 6
Children's neural activity associated with positive > neutral words.

Anatomical location	MNI x	y	z	Size k	Peak T
Frontal					
L Superior frontal gyrus	−18	34	24	4078	8.59
L Anterior cingulum	−2	26	28		6.87
L Precentral	−56	−2	24	964	7.36
L Pars opercularis	−58	10	16		5.25
R Pars opercularis	58	10	20	292	4.95
R Precentral	40	−2	34		4.85
Subcortical structures					
L Thalamus	−22	−16	2	1282	6.87
L Insula	−26	−20	18		6.19
L Hippocampus	−18	−42	8	132	5.91
R Putamen	28	16	0	216	6.64
R Posterior cingulum	16	−34	22	134	6.44

Note. Clusters are presented $p < 0.05$ FWE corrected on the cluster level.

activation in line with the hypothesis was found in bilateral precentral including lIFG (left: $k = 207, z = 3.96, [-52, -2, 26]$, right: $k = 271, z = 4.62, [42, 6, 32]$). Additionally, activation was shown in right thalamus ($k = 162, z = 4.88, [10, -12, 18]$) and in the left pallidum ($k = 308, z = 5.02, [-24, -14, 0]$) on $k = 162$ FWE cluster corrected on $p < 0.05$.

Table 7
Children's neural activity associated with negative > neutral words.

Anatomical location	MNI x	y	z	Size k	Peak T
Frontal					
L Middle orbitofrontal gyrus	−36	44	−2	356	6.64
L Pars triangularis	−46	34	2		5.89
L Anterior cingulum	−20	36	22	295	6.42
L Caudate	−16	14	16		5.09
Subcortical structures					
R Putamen	26	14	0	586	6.15
R Amygdala	24	0	−14		5.20
Parietal					
L Lingual gyrus	−30	−66	2	170	4.77
L Calcarine	−30	−58	14		4.75
L Middle occipital gyrus	−28	−78	12		4.29
Occipital					
R Middle occipital gyrus	34	−76	6	371	5.42
R Angular gyrus	40	−60	32		5.13

Note. Clusters are presented $p < 0.05$ FWE corrected on the cluster level.

Table 8
Children's neural activity for conjunction analysis of positive > neutral and negative > neutral words.

Anatomical location	MNI x	y	z	Size k	Peak T
Frontal					
L Pars triangularis	−46	34	4	243	5.35
L Middle orbitofrontal gyrus	−38	52	−4		4.70
L Anterior cingulum	−20	36	22	212	6.42
L Caudate	−16	14	16		5.08

Note. Clusters are presented $p < 0.05$ FWE corrected on the cluster level.

For negative > neutral words for children compared to adults, activation in line with the hypothesis was found in the insula including amygdala ($k = 340, z = 5.26, [34, 10, -10]$) and for semantic processing, in right superior parietal including angular ($k = 243, z = 5.14, [30, -76, 50]$) and middle occipital ($k = 189, z = 4.29, [36, -72, 28]$) on $k = 189$ FWE cluster corrected on $p < 0.05$.

4. Discussion

This is the first study directly comparing the neural correlates of affective semantic processing in adults and children. Both age cohorts showed a widely distributed activation in the semantic network while performing the VDT. Interestingly, both age cohorts showed activation in bilateral thalamus usually associated with affective processing when all three valence categories were combined. Children showed additional activation in bilateral insula and putamen. Next, valence effects were specifically analysed in children and adults. Both age cohorts showed more strongly distributed activation patterns for positive than for negative words. Here, adults showed stronger activation in structures associated with semantic processing compared to children, whereas children showed activations associated with both, affective and semantic processing. Next, the main findings are discussed in greater detail.

A conjunction analysis over all three valence categories was computed to check whether classical regions associated with auditory lexico-semantic processing reached significance independent of valence. As hypothesised, bilateral superior, left middle temporal, and right middle frontal activation was found in both age cohorts, pointing to auditory semantic processing (e.g., Binder et al., 2009 and Price, 2012 for adults and Weiss-Croft and Baldeweg, 2015 for children). Both age cohorts showed further activation related to auditory semantic processing in right middle frontal activation reported for word retrieval (Price, 2012) and bilateral calcarine sulcus, most certainly associated with tracking auditory stimuli (e.g., Tobia et al., 2012; Cohen et al., 2004). For children additional activation in right precentral and middle cingulate point to word identification within the task (Davis and Gaskell, 2009). In children, these activations were already accompanied by further neural responses in regions hypothesised for affective processing. These encompassed lIFG, ACC, putamen, and insula. This finding was surprising since neutral words were part of this conservative conjunction analysis, and thus, only the shared activation of all three stimuli categories is shown. Likewise, both cohorts showed bilateral thalamus activation usually associated with affective processing (Pessoa, 2018). Consequently, one could assume that at least some 'neutral' words also had an affective potential which is in line with Lebrecht et al.'s (2012) research on micro valences.

To test valence specific effects in both age cohorts, neutral words were subtracted from positive and negative words to identify regions associated with valence processing. In this analysis, disparate neural activation patterns were observed for adults and children. In adults, a widely distributed network of activation was found for positive words in regions associated with semantic processing i.e. left superior frontal, middle temporal, lingual, and right fusiform gyrus (Binder et al., 2009; Friederici, 2012; Hickok and Poeppel, 2007; Price, 2012). Accompanied by insula activation associated with affective processing. All contrasts in adults (conjunction and valence specific) showed significant activation in SMA associated with (auditory) lexico-semantic processing (Hertrich et al., 2016; Lima et al., 2016; Moore et al., 2010). However, compared to the widely distributed activation for positive words, activation for negative words was rather narrow. In line with the hypothesis, adults showed activation in lIFG and right PCC associated with affective processing. Similar to positive words, there was additional activation in right precentral and bilateral SMA. The finding of fewer regions activated for negative stimuli is in line with Hofmann and Jacobs (2014). They presented evidence from neurocomputational modelling showing that positive words are semantically more cohesive (i.e., have more associates) than negative words (cf. Phelps et al., 1997; Maratos et al., 2000; Windmann and Kutas, 2001). Thus, the present data provides further neural support for this idea. In summary, it seems sufficient for adults to activate classic semantic networks to rate the valence of highly familiar words making the recruitment of hypothesised 'emotional areas' (Citron, 2012) such as cingulate or orbitofrontal cortex less likely. A different interpretation is that adults were less affectively involved. To ensure stimulus familiarity for children, words were selected according to their frequencies from a database of children's books. Thus, perhaps these words are less salient and emotionally connotated in the adults' life.

In contrast to the primarily semantic processing in adults during the VDT, the children's data is more in line with previous results found in adults (e.g., Citron, 2012). In fact, children showed activation in regions typically associated with processing of affective words like bilateral IFG, the left ACC, and insula as well as right PCC for positive words. For negative words, left middle OFC, ACC, and lIFG as well as right amygdala activation was found. In the conjunction analysis for both valence categories, children showed significant activation in lIFG extending to the middle OFC and left ACC. As hypothesised for affective processing, children showed similar neural activations (cf. Table 6) as reported in previous studies investigating affective word processing in adults, i.e., in left ACC, right PCC, and lIFG for positive words (Lewis et al., 2006; Maddock et al., 2003; Kuhlmann et al., 2016, 2017). Besides frontal activations in left superior frontal gyrus related to semantic processing and bilateral IFG activation associated with both, affective and semantic processing, the observed activation in subcortical regions indicates that children need to recruit far more neural structures to perform the VDT than adults. In terms of Panksepp's (1998) theory, this would reflect secondary level activation during affective semantic processing as compared to highly automatised cortical processing on tertiary level in adults. This idea is further supported by the activation in thalamic regions as these are thought to integrate affective information from different sensory systems (Koelsch et al., 2015). A similar pattern is observed for negative words. As hypothesised, the activations in left middle orbitofrontal, lIFG, amygdala, and ACC are similar to those of adults reported in previous studies (e.g., Maddock et al., 2003). To summarise the valence specific results in children, one can see a great overlap to previous studies on affective word processing in adults. Also, the conjunction analysis over both valence categories > neutral words showed shared activation in lIFG and left ACC that is in line with the affective semantic processing hypothesis. However, both age cohorts showed extended neural networks in response to positive words, supporting the computational model findings by Hofmann and Jacobs (2014) that predicted larger distributed semantic networks for positive than for negative words. In adults this network is more distributed than in children, confirming our assumption.

Next, semantic affective processing in adults and children was directly compared. Here, the same pattern emerged further supporting the above-mentioned findings: adults showed greater activation in semantic regions while the opposite contrast revealed greater engagement of regions associated with affective semantic processing in children, especially when processing positive words. The conjunction analyses testing for an overlap of activation in adults and children did not lead to significant results. This outcome was not surprising since the adults showed such a different pattern compared to previous research. When looking at the adults' and children's data in light of Panksepp's hierarchical emotion theory (1998) it becomes apparent that children recruit subcortical structures of the secondary system while adults seem to rely on the tertiary cortical system. Thus, adults semantic processing of the present words appears to be significantly shallower than that of children who seem to require deeper affective semantic processing to master the VDT.

To gain further insights into affective word processing in children, several issues need to be tackled in upcoming research. While designing the study, appropriate word stimuli were chosen by using words' valence and arousal values from an adult-database validated by children's ratings. Only words with high frequencies according to a child database were chosen. Thus, the deviating neural pattern observed in adults might be due to the stimulus material differing from that of previous studies. A future solution could be to use separate age-appropriate word lists for children and adults matched for (lexical) properties such as e.g., frequency, length, valence and arousal. Additionally, 1.2 % images of the children's data were interpolated because of movement artefacts. These interpolations can lead to confounds, especially due to the moderate amount of data. Also, mapping six-to-nine-years old children on MNI space validated for adults bears the risk to introduce confounds. These methodological issues need to be addressed for future developmental studies.

5. Conclusions

The analysis of semantic processing revealed clear similarities between adults and children, with children recruiting additional regions associated with word retrieval and identification. This finding could be due to the smaller mental lexicon of children having less semantic associates facilitating word retrieval and identification. The analysis of valence specific activation in adults revealed remarkable differences compared to previous findings: For adults it was sufficient to recruit regions generally associated with semantic processing to successfully evaluate the valence of highly familiar words. This finding supports the idea of valence as a semantic super-feature, even if the adults might not have been as affectively involved. In contrast, children had to recruit regions associated with both semantic and affective processing to successfully access and retrieve a words' valence. Interestingly, the observed valence specific activation in children is similar to previous results found in adults. In sum, we provide first evidence for similar valence processing trajectories irrespective of age on the behavioural and neural level.

Data availability

Behavioral data of the study is available on request to the corresponding author.

Authors contributions

TS and AJ designed the study; TS analysed the data with advice from JL; TS drafted the paper. All authors contributed to the final version of the paper.

Declaration of Competing Interest

The authors declare no competing financial interests.

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