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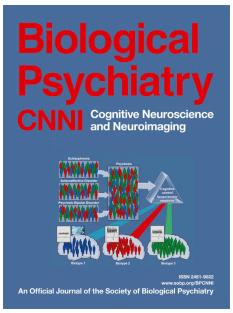

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Neural basis of impaired emotion recognition in adult attention deficit hyperactivity disorder

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Abstract

Background

Deficits in emotion recognition have been repeatedly documented in patients diagnosed with attention deficit hyperactivity disorder (ADHD), but their neural basis is unknown so far.

Methods

In the current study, adult ADHD patients (n=44) and healthy controls (HC) (n=43) underwent functional magnetic resonance imaging (fMRI) during explicit emotion recognition of stimuli expressing affective information in face, voice, or face-voice combinations. The employed experimental paradigm allowed us to delineate areas for processing audiovisual information based on their functional activation profile including bilateral posterior superior temporal gyrus/middle temporal gyrus (STG/MTG), amygdala, medial prefrontal cortex, and precuneus as well as the right posterior thalamus.

Results

As expected, unbiased hit rates for correct classification of the expressed emotions were lower in ADHD patients than healthy controls irrespective of the sensory modality. This deficit at behavioral level was accompanied by lower activation in ADHD patients versus HC in the cortex adjacent to the right STG/MTG as well as the right posterior thalamus which represent key areas for processing socially relevant signals and their integration across modalities. The cortex adjacent to the right pSTS was the only brain region which showed a significant correlation between brain activation and behavioral data (unbiased hit rates).

Conclusions

Altogether these results provide first evidence for a potential neural substrate of the observed impairments in emotion recognition in an adult ADHD. (219 words)

Introduction

Attention-Deficit/Hyperactivity Disorder (ADHD) is characterized by inattention, motor hyperactivity and hyperactivity (1). It interferes with impulse and emotional control leading to impaired social interactions und subsequent mental health problems (2). ADHD was first described in children, but it is meanwhile accepted that it persists into adulthood in roughly every second patient although with partly altered symptomatology (1, 2). Social interaction deficits of ADHD patients are well known (3) and behavioral research documented impaired emotion recognition for facial expressions (4) and prosody in children (5-7) and adults (8-11) with ADHD. Such emotion recognition deficits correlate with attention parameters (11, 12), but inattention cannot fully explain impairments in emotion perception (11) arguing for a social cognition deficit of ADHD patients in its own right (13).

Two imaging studies investigating processing of facial emotions revealed hyperactivation of the amygdalae during overt (14) as well as subliminal presentation (15) while a third study argued for hypoactivation of the amygdala which is modulated by medication with methylphenidate (16). Concerning emotional prosody, a near-infrared spectroscopy (NIRS) study revealed hypoactivation to anger prosody within the right superior temporal gyrus (17) which has been implicated in procession of emotional voices (18). So far, however, it is unknown whether the brain areas responsible for binding emotional information expressed in voice and face (i.e. audiovisual integration areas) exhibit an altered activation profile and to which extent such differences correlate with behavior.

In this study, we examined processing of emotional information presented in voice, face, or face-voice combinations in adult ADHD patients versus healthy controls (HC) using functional magnetic resonance imaging (fMRI). The employed experiment was evaluated in a behavioral study (11) in ADHD patients as well as an fMRI study in HC (19). Thus, we had straightforward hypotheses regarding behavioral effects (i.e. lower recognition rates in ADHD patients versus HC for all emotions) as well as activations in bilateral posterior superior temporal gyrus/middle temporal gyrus (STG/MTG) and right posterior thalamus (19). We specifically investigated whether lower recognition rates of emotions in ADHD patients are accompanied by decreased functional activations in these areas and to which extent activation in these areas correlates with behavior.

Material and methods

Participants

44 patients with ADHD of combined presentation (10 women, mean age ± standard deviation (SD) 30.0 ± 7.0 years) and 43 HC (18 women, 28.2 ± 6.5 years) were included. All participants were German native speakers, right-handed (Edinburgh Handedness Inventory, 20), and had normal or corrected to normal vision. The education was assessed in years not counting repetition of classes. Stimulant medication (methylphenidate: 13 patients, atomoxetine: 2 patients, dexamphetamine: 1 patient) was discontinued for at least five half-life periods. None of the participants were treated with any other psychotropic medication. Patients were recruited via the outpatient clinic of the University Hospital for Psychiatry and Psychotherapy Tübingen. ADHD diagnosis was established on the basis of a clinical interview by a trained psychiatrist or psychologist assessing DSM-V diagnostic criteria for the combined presentation in adults and the self-report questionnaires ADHS-SB ("ADHS-Selbstbeurteilungsskala", 21) and WURS-K ("Wender-Utah-Rating-Scale-Kurzform", 22) as well as third-party anamnesis on childhood symptoms. HC were included if they were never diagnosed with or suspected to suffer from ADHD and were clearly below the diagnostic threshold of any present or childhood ADHD subtype (< 90% of the clinical threshold obtained via questionnaires). Verbal intelligence was assessed using the Mehrfachwortschatztest (MWT-B, Multiple-Choice Vocabulary Intelligence Test, 23). None of the participants suffered from major depression or any other current serious psychiatric condition including drug use, as determined by the German Version of the Structured Clinical Interview (SKID-I, 24). To exclude autistic symptoms all participants completed the Adult Asperger Assessment, 25). Depressive symptoms were captured with the BDI-II ("Beck Depression Inventory", 26). The study was performed according to the Code of Ethics of the World Medical Association (Declaration of Helsinki) and the protocol was approved by the ethics committee of the medical faculty of the Eberhard-Karls-University Tübingen. All participants gave written informed consent prior to participating.

Stimulus material and experimental design

The stimuli were created with the help of professional actors who were videotaped while speaking single German words in a neutral, angry, disgusted, happy, or seductive tone of voice with a congruent facial expression (for more details, see 11). The stimuli were evaluated by an independent group of 31 healthy participants (mean age: 27.3 ± 6.0 years, 16 females). Based on this evaluation we selected the stimuli to guarantee that they are well recognized (minimum recognition rate for each stimulus: 80%) and that recognition rates during audiovisual presentation are balanced across emotions (mean recognition rates: neutral = 93.4%, happy = 95.1%, seductive = 94.1%, angry = 95.1%, disgusted = 95.2%). During three fMRI sessions these stimuli were presented as audiovisual color videos (AV), mute color videos (V), or auditory sound sequences (A) without visual presentation (60 stimuli per modality). During each of the three fMRI sessions 20 stimuli per modality were presented. Participants indicated the expressed emotion on a 5-point circular scale with the German words for “happiness”; “eroticism”, “neutral”, “anger”, and “disgust”. The word “neutral” was placed on top of the circle whereas the two positive connoted expressions “eroticism” and “happiness” where shown on one side and the negative connoted emotions on the other side. To avoid possible laterality effects, the scale was flipped horizontally for half of the participants of both groups. A white dot was randomly placed at one of the five categories and participants had 6 s to choose the response which was fitting best to the expressed affect by moving the white dot clockwise by a button of the response device (see Fig. 1). This design was previously evaluated for application in fMRI studies targeting audiovisual integration (19) and was chosen to remove potential biases from spatial arrangement of response alternatives. While this design effectively removes any association between the number of motor responses and a given category it does not allow to determine omission errors as the randomly chosen starting point of the white dot might already correspond to the category which the participant judges as fitting best to the presented stimulus (and thus this trial requires no response). **The number of trials without motor responses was comparable across the two groups (ADHD: 22.8 ± 1.5, HC: 24.4 ± 1.5, p = 0.22) indicating that there was no systematic bias due to inattention.**

The order of the stimuli within the three imaging sessions was randomized. Stimulus onset occurred on average every 10.5 s (range: 9.0 - 12.0 s) and was jittered in TR/4 with a fixation cross presented in between stimulus presentation. Stimulus presentation and response recording relied on Presentation

software (Neurobehavioral Systems, www.neurobs.com). A screen was placed at the head end of the MRI scanner, visible for participants through a mirror attached in front of their eyes. Sound was presented via MR-compatible headphones. Responses were conveyed using a fiber optic response system (Celeritas Fiber Optic Button Response System, Psychology Software Tools).

Analysis of behavioral data

We evaluated emotion classification accuracy by determining unbiased hit rates (HU, 27) which were obtained for each emotion by multiplying the simple hit rates with their respective positive predictive value to incorporate both sensitivity and specificity of the responses. HU values were arcsine transformed and then submitted to a repeated-measures analysis of variance (ANOVA) with emotion (neutral, happy, seductive, angry, disgusted) and modality (AV, V, A) as within-subject factor and group (ADHD, HC) as between-subjects factor. Gender and BDI scores were included as covariates of no interest. P-values were corrected for effects of non-sphericity (28).

MRI data acquisition

Imaging was performed using a 3 Tesla scanner (Siemens PRISMA, Erlangen, Germany) and a 20 channel head coil. We acquired a high-resolution structural 3D magnetization prepared rapid acquisition gradient echo (MPRAGE) T1-weighted scan (TR = 2.3 s, TE = 4.16 ms, TI = 0.9 s, flip angle 9°, voxel size = 1x1x1 mm^3), a fieldmap for image distortion correction (TR = 0.4 s, TE(1) = 5.19 ms, TE(2) = 7.65 ms, flip angle = 60°, voxel size = 3x3x3 mm^3) and 441 functional images (72 transversal slices acquired interleaved, TR = 1.5 s, TE = 34 ms, flip angle = 70°, voxel size = 2x2x2 mm^3, multiband acceleration factor 3).

Analysis of fMRI data

FMRI data were analyzed with the statistical parametric mapping software (SPM12, Wellcome Department of Imaging Neuroscience, London, UK, www.fil.ion.ucl.ac.uk/spm/software/spm12). Preprocessing included realignment and unwarping to correct for movement as well as static and

movement-dependent field distortions (29), coregistration to the anatomical image, normalization to the standard space of the Montreal Neurological Institute (MNI, resampled voxel size 2x2x2 mm) based on the unified segmentation algorithm (30), and smoothing with an isotropic Gaussian filter of 5 mm full width at half maximum.

Statistical analysis relied on a general linear model (GLM, 31) with three regressors (A, V, and AV trials) modelling presentation of the stimuli with a boxcar function of two seconds duration convolved with the hemodynamic response function. A high-pass filter with a cut-off frequency of 1/128 Hz filtered out low-frequency components. The error term of the GLMs was modelled as a first-order autoregressive process (AR coefficient = 0.2) plus white noise to account for serial autocorrelations.

Contrast images from the first-level GLMs were submitted to second-level random effects analyses. Assignment of activation clusters relied on the automatic anatomical labelling tool (32). We used conjunction analyses (33) to define areas for audiovisual integration $(AV > V) \cap (AV > A)$ using a voxel-wise family-wise error (FWE) corrected height threshold of $p < 0.05$ and a cluster threshold of $k > 25$ voxels. Based on previous research, the regions-of-interest (ROIs) defined by these second-level conjunction analyses were expected to include audiovisual integration areas within bilateral STG/MTG and right posterior thalamus (19). Averaged responses of brain regions delineated by this conjunction analysis were obtained for each subject and submitted to repeated-measures ANOVAs with modality (AV, V, A) as within-subject factor and group (ADHD, HC) as between-subjects factor. Please note that the ROIs were defined by a modality-dependent conjunction analysis and thus the main effect of modality is inevitably significant and therefore only reported for the sake of completeness. This is not the case for the main effect of group or the interaction between group and modality as they are orthogonal to the definition of the ROIs on the basis of the conjunction analysis. Gender and BDI scores were included as covariates of no interest. P-values were corrected for effects of non-sphericity (28). We additionally investigated whether the ROIs exhibited a significant correlation between activation and behavior (HU).

Results

Demographic and psychometric data

Demographic and psychometric data are presented in Table 1. There were no significant differences between the two groups regarding age or educational level, but ADHD patients exhibited significantly lower levels of verbal intelligence as measured by the MWT-B ($p < 0.01$). As expected, significantly higher levels of self-reported problems regarding inattention, hyperactivity, and impulsivity were found regarding childhood (WURS-K) and present symptoms (ADHS-SB) in ADHD patients than HC (both $p < 0.001$). Although none of the participants fulfilled the clinical criteria for a major depressive disorder, ADHD patients exhibited significantly higher scores ($p < 0.01$) for depressive symptoms as assessed by the BDI-II.

Behavioral data

Mean HUs depending on the sensory modality and emotion are shown in Fig. 2 for ADHD patients and HC (grey and white bars, respectively). The repeated-measures 5x3x2 ANOVA with emotion (neutral, happy, seductive, angry, disgusted) and modality (AV, V, A) as within-subjects factor and group (ADHD, HC) as between-subjects factor as well as gender and BDI scores as covariates of no interest revealed a significant main effect of emotion ($F(4, 328) = 6.56$, $p < 0.001$), modality ($F(2, 164) = 31.75$, $p < 0.001$), and group ($F(1, 82) = 4.65$, $p < 0.05$). The main effect of emotion was due to the fact that HUs (averaged across modalities and groups) were significantly higher (all $T(86) > 4.54$, all $p < 0.001$) for stimuli expressing happiness (70 ± 1 %) and seduction (70 ± 2%) than anger (62 ± 1 %), disgust (65 ± 1 %), or neutrality (64 ± 1 %). The main effect of modality was due to higher HUs (averaged across emotions and groups) for AV stimuli (82 ± 1%) than V stimuli (69 ± 1%) and A stimuli (47 ± 1%). All statistical comparisons across the three modalities were significant (all $T(86) > 11.57$, all $p < 0.001$). The main effect of group was driven by significantly ($T(85) = 2.49$, $p < 0.05$) lower HUs (averaged across emotions and modalities) in ADHD patients (64 ± 1%) than HC (69 ± 2%). There was a significant interaction between emotion and modality ($F(8, 656) = 4.54$, $p < 0.001$). This interaction reflected significantly higher HUs (averaged across groups) for AV and V stimuli expressing happiness than the other four categories (all $T(85) > 2.55$, all $p < 0.05$) while seduction was significantly better recognized than the other four categories for A stimuli (all $T(85) > 10.4$, all $p < 0.001$). None of the interactions including the factor group were significant.

fMRI data

In agreement with our a priori hypothesis, the conjunction analysis revealed significant activations in bilateral STG/MTG and right posterior thalamus. In addition, bilateral hippocampus/amygdala, medial superior frontal gyrus (SFG), precuneus, and gyrus rectus as well as right temporal pole were identified in this analysis (see Fig. 3 and Table 2).

The repeated-measures 2x3 ANOVA revealed a significant main effect of modality (all $F(2, 162) > 4.68$, all $p < 0.05$) in all ROIs which is to be expected as the ROIs were defined by a modality-specific effect. A significant main effect of group was only found in right STG/MTG ($F(1, 81) = 6.34$, $p < 0.05$) and right thalamus ($F(1, 81) = 4.79$, $p < 0.05$) which was due to lower activation in ADHD patients than HC (see Fig. 2, all $T(84) > 3.30$, all $p < 0.05$). None of the other brain areas delineated by the conjunction analysis exhibited a significant main effect of group (all $F(1, 81) < 1.32$, all $p > 0.38$). There was no interaction between modality and group in any of the ROIs (all $F(2, 162) < 2.41$, all $p > 0.13$). The only brain area which showed a significant correlation between activation and Hus was the right STG/MTG. In this brain area, the correlation between activation (beta estimates) and HUs was $r = 0.18$ for AV and V trials as well as $r = 0.22$ for A trials (all $p < 0.05$). Separate analyses for ADHD patients and HC revealed that these correlations are mostly driven by the control group for AV trials (HC: $r = 0.38$, ADHD: $r = -0.07$) and A trials (HC: $r = 0.28$ and ADHD: $r = 0.09$). For V trials similar correlation coefficients were observed in both groups (HC: $r = 0.16$, ADHD: $r = 0.14$).

Discussion

To our knowledge, this is the first neuroimaging study investigating the neural basis of emotion recognition in adult ADHD patients. We utilized an explicit emotion categorization task (19) and presented emotions in different sensory modalities (facial expressions, prosody, and their combination) allowing us to delineate key areas for emotion processing including posterior STG/MTG, thalamus, and amygdala. Adult ADHD patients exhibited diminished activation in the right posterior STG/MTG and the thalamus suggesting that processing of emotions is disrupted both in

early and late processing. The only ROI showing a correlation between recognition rates and activation was the right STG/MTG suggesting its activity has direct consequences for behavior.

Behavior

Participants identified audiovisually presented emotions better than auditory or visual stimuli alone. This enhanced performance when combining auditory and visual emotional information is a well-established finding (11, 19, 34, 35) as the combination across modalities yields richer information. Thus, reductions of the uncertainty translate to better accuracy in task performance (36). There is initial evidence that this cross-modal effect might not result from "post-perceptual decision under attentional control" (34), but instead reflects an early-on integration process (36, 37) with a limited role of awareness.

It should be noted, that the emotion recognition rates obtained in this study during fMRI were lower than in a previous behavioral study (11) which is most probably due to distractions caused by the scanner noise and the less comfortable situation. The main result with lower recognition rates in ADHD patients than HC, however, was replicated. This emotion recognition deficit in ADHD was not confined to a specific emotional category. Although this is in line with recent work (11, 38), previous meta-analyses suggested that patients with ADHD show a robust deficiency in recognizing negative emotions, particularly for anger and fear (13, 39). This observation is typically discussed as a deficit in decoding cues that signal socially relevant negative feedback (e.g. 40). There are several aspects that could explain the discrepancy to our results. First, we did not include fear stimuli as we decided to choose emotions with strong relevance for social interactions rather than those signaling threat-related information important for survival. However, no bias for anger was found in our study either. Secondly, most of the studies on this topic employed several negative emotions (5, 41-43), but only one positive emotion (i.e. happiness, for a discussion on this issue, see 44). This represents a possible confound as it requires discrimination between distinct categories of negative, but not positive emotions. We avoided such confounds of emotion-specific differences in task difficulty by including the same number of positive and negative stimuli/categories and using stimuli with similar recognition rates across emotions (11). In line with these previous findings, our behavioral results suggest that the

emotion independent performance decrement in ADHD might reflect a general sensory encoding deficiency (11) which occurs similarly for all emotions used in our study.

Activation

The experimental design was adapted from a previous fMRI study in HC (19) which identified bilateral posterior STG/MTG and right thalamus as central nodes for processing facial and vocal emotions. We replicated these findings, but also delineated significant results for medial SFG, precuneus, and gyrus rectus as well as right temporal pole which is most probably due to the higher statistical power provided by a larger number of participants (87 versus 24 subjects) as well as higher signal-to-noise ratio afforded by a higher field strength (3T versus 1.5T) and faster sampling (TR = 1.5 s versus 2.0 s) by using multiband EPI. The only ROIs that showed a significant difference with lower activation in ADHD patients, however, were the right posterior STG/MTG and the right posterior thalamus. The posterior STG/MTG has consistently been reported to be involved during audiovisual integration of facial and vocal information (19, 35, 45, 46). Furthermore, audiovisual percepts, such as the McGurk illusion, depend on the activation level in this area (47) and can be disrupted by means of transcranial magnetic stimulation (TMS, 48). While this suggests that the posterior STG/MTG is involved in audiovisual integration, there is also evidence that it participates in attentional processes (49-51) and shifts of attention to social cues (52, 53). As hypoactivation within this area and emotion recognition deficits of ADHD patients were not confined to the bimodal condition, but similarly occurred for the two unimodal conditions, this finding might rather reflect deficient allocation of attentional resources to relevant cues than disrupted audiovisual integration. The same pattern of brain activation was observed in the right posterior thalamus indicating that altered brain activity is not restricted to higher-order areas, but arises also in early processing stages. This is in excellent agreement with electrophysiological studies indicating alterations of early and late event-related potentials (ERP, 54, 55) during processing of facial emotions in ADHD patients.

Two previous fMRI studies described increased activation (14, 15) while a third reported diminished activation within the amygdala (16) of ADHD patients. In our study, no significant difference in activation was found within the amygdala. A likely explanation for these discrepant findings across

studies is the nature of the employed tasks as it is long established that the amygdala show activation differences during implicit versus explicit processing (56, 57) or rating of self- versus other-related emotions (14). However, other differences in study design including participants (adults versus children or adolescents), stimuli (dynamic videos versus photographs), and employed emotions might also contribute to variability of amygdalar responses across studies.

Association between behavior and activation

Better emotion recognition was related to higher activations in the posterior STG/MTG in HC replicating previous results (19). This relationship between activation and behavior was not confined to audiovisual stimuli, but also occurred for auditory and visual stimuli. A possible explanation for this observation is that electrophysiological results obtained in multisensory regions of the macaque revealed that only a minority of about 20% of cells within these areas are sensitive to stimuli from more than one modality (58, 59) and that high-resolution fMRI revealed that the posterior STG/MTG has a patchy organization of unimodal and multimodal units (45). Furthermore, neuroimaging data revealed that sharpening of neural responses as measured by repetition suppression (60) within this area occurs also for unimodal and bimodal stimuli (35). In contrast to HC, ADHD patients did not show a significant association between behavior and activation levels of the right posterior STG/MTG. This finding is in line with NIRS data indicating that ADHD patients exhibit a higher variability of oxygenated hemoglobin within this area during perception of emotional faces (61). Unfortunately, this NIRS study was based on a passive viewing paradigm making it impossible to draw conclusions with respect to behavioral consequences of this phenomenon.

Our findings showing a relationship between activity in the right STG/MTG and emotion recognition nicely dovetails with electrophysiological results indicating that late ERP components, such as the P3, correlate with behavioral measures obtained during emotional face perception (55). We believe that a relationship between brain activation and behavior is the strongest evidence which fMRI alone can provide for the assumption that a certain brain area is implicated in a cognitive process. Further evidence for a causal involvement requires combination with other methods, such as TMS, to show that disruption of activity impacts behavior (48). It has, however, been pointed out that altered

activation without concurrent behavioral effect might still provide complementary information about 'hidden' processes not observable by traditional behavioral measures (62). Thus, we do not propose that the lack of a correlation between activity in the right posterior thalamus and emotion recognition signifies that diminished activity in this area is irrelevant. It is possible that disrupted activity in early regions could affect downstream processing areas which might explain why the correlation between activation and behavior in the posterior STG/MTG was observed for HC, but not ADHD patients.

Limitations

It should be noted that ADHD patients were recruited from an outpatient clinic dedicated to diagnosing adults first-time. We took careful measures to ensure relevant symptoms were present in childhood, including primary school certificates encompassing descriptions of behavior. Nevertheless it is possible that the ADHD patients included in this study were milder affected than their peers diagnosed in childhood right away as they did not require consultation until facing heightened environmental demands in adulthood. Our screening for comorbid disorders relied on the SKID-I. None of the participants showed any clinical sign for intoxication, but future studies could still include toxicological screenings to rule out any alcohol or drug use and employ SKID-II screenings to determine whether activation is additionally influenced by personality factors. Finally, inclusion of patients with other psychiatric disorders could determine whether our findings are specific for ADHD.

Conclusion

To our knowledge, this is the first fMRI study investigating the neural basis of impaired emotion recognition in ADHD. Overall, our findings indicate that ADHD patients exhibit a general deficit in emotion recognition which occurs irrespective of sensory modality or emotional category and relates to hypoactivations in both an early (right posterior thalamus) and a late (right posterior STG/MTG) brain region. In line with previous electrophysiological results activation in the late, but not the early sensory processing region correlated with behavior pinpointing to the right posterior STG/MTG as a potential neural correlate mediating behavioral consequences. (4000 words)

Financial Disclosures

The authors report no biomedical financial interests or potential conflicts of interest.

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Tables:

Table 1: Demographic and psychometric data

	ADHD	HC	
	Mean ± SD	Mean ± SD	two-tailed p
Age	30.0 ± 7.0	28.2 ± 6.5	0.21
Educational years	15.9 ± 3.1	16.6 ± 2.4	0.25
	Mean ± SEM	Mean ± SEM	one-tailed p
WURS-K	43.2 ± 2.0	8.3 ± 0.9	1.5×10^{-23}
ADHD-SB	31.8 ± 8.0	5.5 ± 4.2	4.0×10^{-29}
BDI	7.0 ± 1.1	1.8 ± 0.3	8.7×10^{-3}
MWT-B	101.3 ± 1.6	107.4 ± 1.9	9.4×10^{-3}

ADHD: Attention deficit hyperactivity disorder, HC: Healthy Controls, SD: Standard Deviation, SEM: Standard error of the mean

Table 2: Brain areas showing a significant audiovisual integration effect (AV-A ∩ AV-V)

Anatomical Definition	**MNI coordinates**	**Z score**	**cluster size**
Right STG/MTG	48 -38 8	6.58	266
Bilateral medial SFG	6 56 34	6.50	253
Left hippocampus/amygdala	-22 -12 -14	6.42	57
Right posterior thalamus	14 -30 -2	6.38	28
Left STG/MTG	-58 -56 12	6.22	288
Right hippocampus/amygdala	22 -16 -14	6.04	47
Bilateral precuneus	0 -58 36	5.97	136
Bilateral gyrus rectus	2 46 -18	5.90	26
Right temporal pole	48 16 -32	5.81	56

STG: superior temporal gyrus, MTG: middle temporal gyrus, SFG: superior frontal gyrus, MNI: Montreal Neurological Institute

Figure legends:

Figure 1: Task design. Stimuli, balanced for experimental condition (A, V, AV) and emotional category were presented across three imaging sessions with 60 trials each. Stimuli were presented in randomized order within sessions. Inter stimulus intervals ranged from 9-12 s and subjects had 6 s to choose a response. The classification task was performed on a circular scale with five emotional categories ("EROTIK"=eroticism/seduction, "FREUDE"=happiness, "EKEL"=disgust, "ÄRGER"=anger, "TRAUER"=sadness, "NEUTRAL"=neutral). In order to avoid possible laterality effects, the scale was flipped horizontally for half of the participants of both groups.

Figure 2: Emotion identification performance (unbiased hit rate ± standard error of the mean). ADHD subjects exhibit poorer performance than healthy controls across all emotions (H: happy, E: erotic/seductive, D: disgusted, and A; angry) and modalities (right panel: unimodal acoustic, center panel: visual, and left panel: audiovisual).

Figure 3: Conjunction analysis AV – A ∩ AV – V. ADHD patients exhibited lower levels of activation in the right posterior STG/MTG (left panel) and right posterior thalamus (right panel). Activation levels in the right posterior STG/MTG were positively correlated with the emotion identification performance, most prominently within the auditory-visual condition. These effects were mostly driven by the performance of healthy controls (center panel).

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