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ARTICLE

Choice matters: Pupils' stress regulation, brain development and brain function in an outdoor education project

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Abstract

Background: Education outside the classroom (EOtC) is considered beneficial to children's physical and mental health. Especially, stress resilience has been linked to nature experience.

Aims: This study experimentally explored the effects of pupils' autonomy support (AUT) and physical activity (PA) on their biological stress responses and brain development in EOtC.

Sample: The study comprised 48 fifth and sixth graders.

Methods: The intervention consisted of one day/week taught in a forest over one school year. Structural magnetic resonance imaging (MRI) was conducted at the beginning and the end of the school year, functional MRI under a stress condition at the end. Regions of interest were amygdala, hippocampus and the anterior cingulate cortex (ACC). All other measures were obtained at the beginning, at mid-term and at the end of the school year. PA was measured using accelerometry. Cortisol levels were obtained three times during the examined school days. AUT was measured with a paper-based survey. Data were analysed using Bayesian multivariate models.

Results: EOtC students exhibit more efficient regulation of biological stress-reactivity and show a reduction of cortisol over the day associated with light PA in the forest. Cortisol is further associated with amygdala activation in the stress condition. Cerebral structural change is best explained by age; however, AUT has a positive direct effect on the maturation of the ACC, which is stronger in EOtC.

Conclusions: Our results support the idea that autonomy supportive teaching fosters cerebral maturation and that EOtC can have a positive effect on biological stress regulation.

KEYWORDS
stress regulation, resilience, outdoor schooling, MRI, Cortisol, physical activity, accelerometer

INTRODUCTION

Stress in adolescence and the alienation from the natural world

Children and adolescents are under great pressure with respect to mental and physical conditions. Not only do they have to cope with rapid biological changes in their bodies and with insecurity due to growing independence and new experiences. Also, youngsters are confronted with the consequences of rapid globalization and increased use of technology and urbanization (United Nations, 2019). This development challenges mental health and results in a decrease of the population's physical activity (PA). Worldwide, 10–20% of children and adolescents experience mental disorders. Half of all mental illnesses begin by the age of 14 (WHO, 2012). Moreover, three in four adolescents do not currently meet the WHO's global recommendations for PA. This development goes hand in hand with the alienation from the natural world. More and more people, especially children and adolescents, have less and less contact with nature. Data from the United Kingdom, the United States of America and Japan indicate that the percentage of children who play in natural areas dropped from 80% some 40 years ago to less than 10% today. This appears to contribute to degradation of public health and well-being with rises in prevalence of obesity, attention disorders, depression, anxiety or sleep disturbances (Soga & Gaston, 2016). Moreover, adolescence is the critical age when nature-connectedness is lowest in the whole life span (Hughes et al., 2019). Together with a trend of increasing academic pressure in schools (OECD, 2017), this has negative effects on the students' learning capacity and academic performance (UNESCO, 2012), and a vicious circle is spun leading to even more distress in adolescence (Pascoe et al., 2020). It has been well established in recent research that children and adolescents are physically more active in natural environments than in comparison conditions (Bentsen et al., 2021; Bølling et al., 2021; Schneller et al., 2017) and show higher levels of self-esteem and self-efficacy (Barton et al., 2012, 2015; Roberts et al., 2019; Tillmann et al., 2018). Additionally, research within Stress Reduction Theory (SRT) (Ulrich, 1983) has shown mental and social health benefits of immersive nature experiences, especially with respect to stress resilience, if to a lesser degree (Mygind et al., 2019). The current study is situated within SRT and contributes to the literature with empirical data on children's biological stress regulation and brain development in an outdoor educational setting.

Stress reduction, self-determination and outdoor schooling

SRT uses an evolutionary framework and suggests that the bodily make-up of the human species has evolved over 300,000 years ago in natural environments, and only a small proportion of our history has occurred in more urbanized societies. This evolution has calibrated our senses and bio-physiological responses to the numerous stimuli in the natural world and might also have 'left a trace on our collective psyche' (Schertz et al., 2021). p. 12, which results in a positive response towards natural environments. Research in SRT follows two major strategies: The first looks at long-term effects in cross-sectional surveys, for example comparing people living in more- and less-green neighbourhoods with regard to subjective levels of stress (Nielsen & Hansen, 2007; Stigsdotter et al., 2010; Ward Thompson et al., 2016) or ability to cope with stressful life events (van den Berg et al., 2010). The second is experimental and builds on intervention programs that expose subjects to stressful stimuli with and without nature contact and measure acute bio-physiological responses. Of the 26 studies included in the latest meta-analysis on SRT (Mygind et al., 2019), 14 studies included cortisol measures, twelve used heart rate variability

measures (HRV) as a stress indicator, four studies included alpha amylase, four adrenaline or noradrenaline and one study measured activity in the prefrontal cortex and its haemoglobin concentration. In six studies, cortisol measures were combined with HRV. Of those recent SRT studies, more than 50% were performed on college students, that is implying a serious population bias and thus limiting the general ecological validity of the theory; only two studies involved children and adolescents in the school context of which only one is relevant for this study, and it is in fact based on the same data as this article: Children profiting from regular outdoor schooling in a forest nearby the school one day per week showed a significant decrease of cortisol values on the days of the outdoor teaching, with medium effect sizes, $\eta^2 = 0.103$ (Dettweiler, Becker et al., 2017). Further analyses could link this decline with light PA (LPA) in a forested area (Becker et al., 2019).

This adds to the recently reported beneficial effects Education Outside the Classroom (EOtC) seems to have on pupils' physical, mental and social well-being (for review, see Remmen & Iversen, 2022 and Becker et al., 2017), which is partially explained with outdoor classrooms offering greater affordances for self-determined behaviour than indoor classrooms do (Bølling et al., 2018, Dettweiler, Lauterbach et al., 2017). This is insofar interesting for stress regulation as there is a direct link between well-being and self-determination, and both are implicated in the stress coping process (Ntoumanis et al., 2009). Within Self-Determination Theory (SDT), human behaviour is understood as a dynamic person-environment relationship that impacts on emotion and cognition. SDT proposes three fundamental and universal human needs, that is perceived autonomy and competence support as well as relatedness, whose satisfaction is essential for individuals' personal growth and development. Hereby, autonomy plays a central role in behavioural regulation (Deci & Vansteenkiste, 2004): The more self-determined or autonomous humans perceive themselves, for example the more choices pupils can make in school, the better is their socio-psychological well-being (Deci & Ryan, 2000).

However, despite convergent results with stress reduction through nature immersion across the studies and theories, evidence for the different psychological pathways of SRT in nature is still sparse, especially for children and adolescents. To the best of our knowledge, no previous study has investigated pupils' biological stress regulation and cerebral maturation with respect to educational parameters, such as perceived autonomy support in different teaching contexts, using SRT and SDT as frameworks.

Biological stress regulation and maturation

How strongly people react to stress is influenced by how well their brain is able to modulate biological stress reactions in stressful situations. Stress reactions are primarily initiated by two physical stress systems. The first system is based on the activation of the sympathetic nervous system and is associated with an increased release of adrenaline and noradrenaline. The second system is the so-called 'hypothalamic–pituitary–adrenal axis' (HPA axis). Associated with the HPA axis are three particular brain regions, the hippocampus, the amygdala and the anterior cingulate cortex (ACC), which are part of the limbic system. The amygdala regulates emotional behaviour, whereas the hippocampus is more associated with learning and memory (Lupien et al., 2009). However, hippocampus and amygdala both have reciprocal connections and influence each other. Since the hippocampus has projections to hypothalamus, it can affect the release of cortisol (Anand & Dhikav, 2012). The ACC is involved in a number of higher-level functions, such as attention allocation, reward anticipation, decision-making and regulation of emotions (Bush et al., 2000). The activation of all three regions has been found to covary with cortisol responses during the processing of a stress test (Henze et al., 2020) (Figure 1).

In particular, the HPA axis is thought to play an important role for the development of mental disorders. Chronic stress in childhood, for example, has been associated with increased stress-reactivity and depressive symptoms in later life (Heim et al., 2000). For example, early life stress assessed by childhood basal cortisol function has been shown to be associated with adolescent amygdala function, emotional reactivity and psychopathology, which might be related to changes in prefrontal control networks (Burghy et al., 2012, 2016). Structural brain changes after chronic stress exposure can also be found in animal

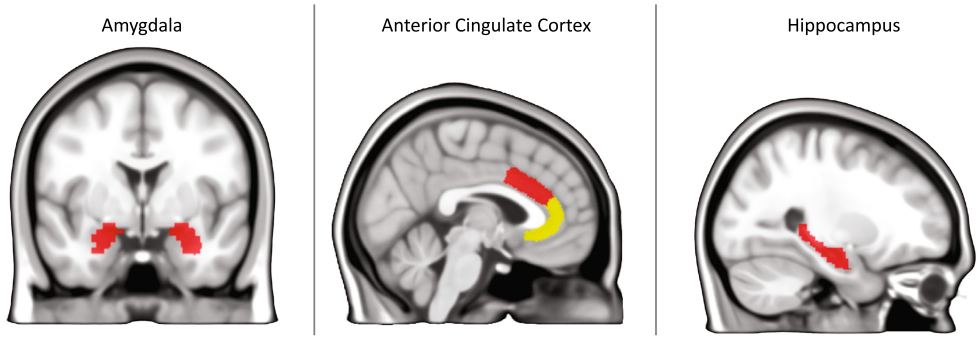

FIGURE 1 Brain regions of interest (ROI) in the limbic system: Amygdala, rostral ('lower' part, in the online version: Yellow) and caudal ('upper' part, in the online version: Red) anterior cingulate cortex (ACC) and hippocampus

experiments, especially in brain structures such as the hippocampus. However, in human studies of adolescents who suffered from chronic stress, this relationship does only show up delayed: Here, the effect, a reduction in volume, is only found in adulthood (Andersen & Teicher, 2008). A brain structure that shows an immediate structural change after chronic stress is the ACC (Cohen et al., 2006). The ACC is known to have a regulatory effect on the HPA axis, as well as on emotion-relevant limbic structures such as the amygdala. Hereby, the rostral part of the ACC, the rACC, is associated with cognitive control and choice of action (Jiang et al., 2015). The caudal part of the ACC, the cACC, is associated with motor planning and action execution (Morecraft et al., 2012). There are no clearly defined borders between those parts based on their anatomical connections (Tang et al., 2019); however, the literature reports different structural changes in those parts in stress adaptation (Bryant et al., 2008).

With respect to the functionality of the ACC as a whole, it was shown that its activity under stress is modulated by the environment participants grew up in childhood (Lederbogen et al., 2011). Those who had spent their childhood in a rural area show a lower activation of this structure under acute social stress than those who grew up in a big city. Bratman et al. (2015) have demonstrated that a 90-minute stay in nature alone leads to a reduced activation in this stress-sensitive brain structure, which was accompanied by a decline in rumination. Rumination is a cognitive thinking style that is viewed as a risk factor for depression and also occurs more frequently in depression (Nolen-Hoeksema, 2000).

Recently, is was demonstrated that exposure to an urban green space was related to lower level of negative affect. This lower negative effect in turn was correlated with prefrontal cortex, including ACC, activation during processing of negative emotions. Interestingly, this relation was particularly pronounced in inhabitants of urban areas with low amounts of green spaces and high prevalence of mental disorders (Tost et al., 2019).

The connection between staying or growing up in nature and stress-associated brain regions seems to apply not only to the activation of these regions, but also to their structure. Haddad et al. showed that the brain volumes of both the ACC and the prefrontal cortex in men are associated with the type of location where they grew up. The authors found that adults who grew up in rural areas have greater brain volume in these two structures (Haddad et al., 2015), a finding that fits well with the above-mentioned findings by Cohen et al. (2006). However, these findings were revealed in adults. In childhood and adolescence, due to the ongoing maturation, a direct relation between volume and function cannot be drawn.

In children aged 10–12, the maturation of the brain is rather complex and follows very individual trajectories. During the adolescent years, hippocampus (Tamnes et al., 2018) and amygdala (Scherf et al., 2013) generally increase in volume, whereas cortical thickness decreases (Walhovd et al., 2017). Particularly the prefrontal cortex including the ACC shows a rather late maturation and a constant reduction of thickness until the end of the adolescence around the age of 20 (Gogtay et al., 2004).

Research gap and rationale

Despite the long-established link between motivational theory and stress coping, there is a gap in the literature in children's and adolescents' (biological) stress regulation in the educational context. And since EOtC has been associated with significantly higher self-regulated motivational behaviour within SDT, and since SRT explains stress reduction in natural environments, we hypothesised that EOtC has the potential to positively affect the pupils' stress levels. We thus were interested to explore if the regular exposure to natural environments and the degree of perceived autonomy support in an outdoor education intervention had any effect on the children's (1) biological stress regulation during the lessons, (2) their changes in brain structure over the school year, and (3) their brain function under a stress test after one school year in the respective teaching condition. The brain regions of interest (ROI) were the hippocampus, the amygdala and the ACC, which are especially related to stress regulation.

MATERIALS AND METHODS

Study design and intervention

The study was a longitudinal control group design. The participants attended a private secondary school in Heidelberg, one of the few schools in Germany practicing regular and compulsory outdoor schooling.

Teaching intervention

The quasi-experimental EOtC-intervention consisted of one school day per week in the forest, with 5×45 min 'science classes' and 1×45 min 'physical education' (PE) allocated over the school day. The control group attended normal indoor lessons. As can be seen in Table S1, there are two major differences between the intervention and the control conditions: (1) the EOtC curriculum is taught in cross-disciplinary units, whereas it is taught in segments, subject by subject, in the control group; this pedagogical approach of the EOtC program invites the pupils (2) to autonomously use the space in which the teaching is going on (Mall et al., 2021). In contrast, the pedagogical frame for the control group is based on traditional indoor teaching concepts with less opportunities for individual decisions and potentially less variability. Thus, the pupils' perceived autonomy conceived as choices they could make is expected to be higher in the intervention group as part of the experimental condition. With respect to the cognitive load and academic demand, we consider the intervention and the control conditions to be equivalent since the content of the curriculum is not different between the indoor and the outdoor teaching groups. To answer research question (1), we analysed the children's cortisol trajectories over each of the three school days in each group. For research question (2), we aggregated the data across the three measurement occasions in order to analyse the trajectories over the school year.

Montreal imaging stress task

For research question (3), we conducted an adapted version of the Montreal Imaging Stress Task (MIST; [Dedovic et al., 2005]) at the end of the school year, in both intervention and control groups. Hereby, the participants had to solve arithmetic tasks under time pressure and received negative social feedback. The difficulty of the arithmetic tasks was adjusted to the educational level of the pupils and consisted of tasks common for the 5th and 6th grade. The tasks were assigned to different difficulties. The experiment had a block design and consisted of three conditions: a rest, a control and a stress condition. During the rest condition the word 'Pause' (German for 'break') was shown on the task display and no response was required. During the control conditions arithmetic tasks were presented and the answer was given

by rotating and confirming a selector on a circular answer field with the digits 0–9 with button presses and feedback was given whether the answer was correct. In the stress condition in addition to the arithmetic tasks, a growing bar representing a time limit and arrows indicating individual performance and 'expected' (perfect) performance were shown. Further, the difficulty of the tasks was adapted to the performance. The experiment was conducted in two consecutive runs with negative verbal feedback about the performance between the two runs. Before the experiment, pupils were informed about the arithmetic tasks, and after the experiment, they were debriefed that the negative feedback they received was not related to their actual performance and that the goal of the experiment had been to evoke a stress response. The two parts of the experiment were modelled together and the contrasts *stress* > *rest* and *stress* > *control* were estimated over both parts. The interpretation of the contrast estimates is straight forward: greater values refer to more activation of the respective region of interest in the respective direction. In accordance with the task demands of the MIST, the contrast *stress* > *rest* is expected to be greater than *stress* > *control*.

Participants

We recruited 48 pupils (41% female) into the study, 37 in the intervention group and 11 in the control group. Pupils in the control group were on average 6 months older. This imbalance was a consequence of last-minute changes to the design after the school had decided to accommodate parents' demands for a third outdoor class rather than sticking to the original plan with two. As of normal occurrence, some pupils were absent from school during data collection, which accordingly lead to missing data. Table 1 summarizes the enrolment data. The socioeconomic status can be considered similar.

Measures

Physical activity

PA was obtained using triaxial Axivity AX3 acceleration sensors (Axivity Ltd., Newcastle upon Tyne, United Kingdom). One sensor was attached to each child's back above the upper point of the posterior iliac crest, with the aid of a medical tape. The sensors were worn between 08:30 a.m. and 12:30 p.m. during school time at the three measurement occasions at the beginning, at mid-term and at the end of the school year. In this study, we were only interested in LPA, that is the proportion of LPA from 8:30 a.m. to 10:30 a.m. (LPA2) and from 10:30 to 12:30 p.m (LPA3).

Cortisol

Salivary cortisol is measured in μg/L and was obtained using Cortisol-Salivette™ collection tubes (Sarstedt, Nümbrecht, Germany) at time points 08:30 a.m., 10:30 a.m. and 12:30 p.m. at the three measurement occasions. For the analysis of the cortisol trajectories over the school days, we used log-transformed raw values from the respective time points. For the analysis of the structural changes in the brain and its functioning under stress, the difference values $Cort3 - Cort1$ were averaged over the three measurement occasions, beginning, midterm and end of the school year.

TABLE 1 Enrolment data

	N	Beginning	Midterm	End of school year
Total	48	46	45	46
Intervention	37	35	35	35
Control	11	11	10	11

Magnetic resonance imaging (MRI)

Structural changes in brain structures and functional responses in the brain to the MIST have been measured with magnetic resonance imaging (MRI) technology. Cortical thickness is measured in *mm*, volume in *ml*. The pupils were invited to an examination at the Central Institute of Mental Health in Mannheim, Germany, at the beginning and at the end of the school year. At the latter time point, the adopted MIST was administered to the pupils.

Perceived autonomy support

Perceived Autonomy Support is conceived as the pupils' choicefulness, a subscale in an adapted version of the Basic Psychological Need Satisfaction Scale (BPNS) within SDT (Deci & Ryan, 2000). The data were collected at the three measurement occasions with a paper-based survey. The autonomy-scale consists of eleven items and is divided in three sub-scales, asking for 'ascertained respect', 'possibilities of choice' and 'comprehended reasons'. Only the four items related to 'choicefulness' were robust enough to hold measurement invariance and could be operationalized in the statistical models as a composite score, averaged over the three measurement occasions. The structural validity over the three measurement occasions is excellent (*CFI* = 1.00, *TLI* = 0.99) and reliability can be deemed acceptable to good (Cronbach Alpha reliability scores: $a = 0.74$ at the beginning, $a = 0.82$ at midterm, $a = 0.79$ at the end of the school year).

See Figure 2 for an overview of the study variables and the data collection plan. More detailed technical information on the measures can be found in the supplementary material, section 1.

Data analytical approach

Analysis of cortisol trajectories

We estimated the growth-rates of cortisol in a Bayesian multiple group latent growth model (LGM) with LPA as a time-variant covariate, controlled for seasonal effects (slope and intercept regressed on season).

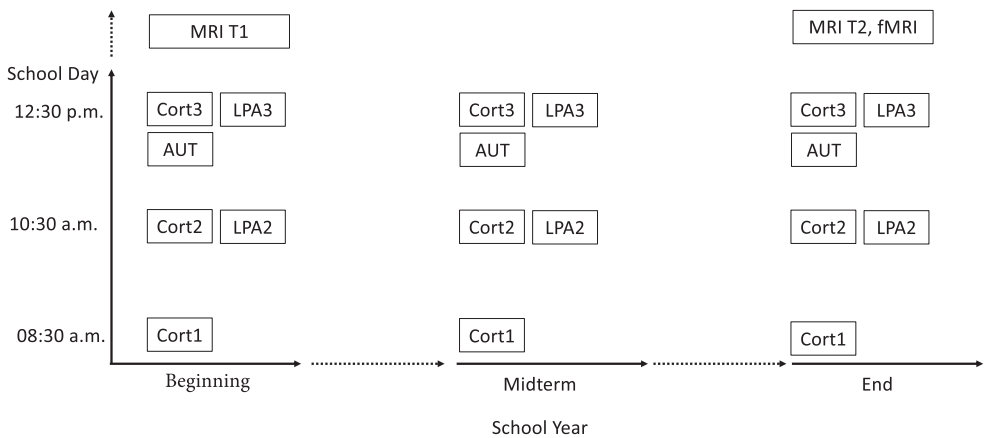

FIGURE 2 Study variables and design. Cort: Salivary cortisol; AUT: Perceived autonomy support/choicefulness; LPA: Light physical activity; MRI: Magnetic resonance imaging; fMRI: Functional MRI. Cort, AUT and LPA have been collected at three time points during a school day, depicted at the y-axis, at three measurement occasions during the school year, depicted at the x-axis. MRI was conducted at the beginning and the end, fMRI only at the end of the school year after the school day

Analysis of structural brain data

In order to determine the effect of group affiliation and perceived autonomy support/choicefulness as well as cortisol-differences during classes averaged over the school year on the maturation of the respective brain region, controlled by gender and age, we fitted a Bayesian multivariate regression model.

Analysis of brain functioning

Data from the MIST on the pupils' brain functioning were statistically analysed with Bayesian regularized regression models with the respective contrasts *stress > rest* and *stress > control* in the respective brain regions as response variables. Group affiliation is the experimental condition variable, perceived autonomy/choicefulness is the pedagogical predictor variable, the difference-score of cortisol during classes is the biological predictor variable, and age and gender are covariates in the models.

Additional technical information and computer code can be found in the supplementary material, sections 2 and 3.

FINDINGS

Biological stress regulation during classes

Table A1 in Appendix A presents the descriptive statistics of the study variables for the growth trajectories of cortisol over the school days. When freely estimated, cortisol values at 8:30 a.m. (intercept) are very individual among all pupils in both groups, and the slope parameters have no decisive sign. There is no seasonal effect, neither on the starting values at 8:30 a.m., nor on the slopes. Pupils in the intervention group tend to have negative slopes, which indicates a decrease of cortisol levels in the children's sputum over the school day with a probability of more than 60%. Pupils in the control group tend to have positive slopes. The time specific effects of LPA on the cortisol levels are very interesting: in the intervention group, the slope parameters for both time periods, from 8:30 a.m. to 10:30 a.m. and from 10:30 a.m. to 12:30 a.m., are decisively negative, with medium effect sizes (standardized mean of the regression coefficient β for 08:30 a.m. to 10:30 a.m. $\beta = -0.29$, $sd = 0.11$ and from 10:30 a.m. to 12:30 a.m. $\beta = -0.27$, $sd = 0.11$). LPA explains between 23 and 60% of the variance in the cortisol levels at the respective time points in the two groups. Thus, LPA can be credibly deemed the driver for the decrease of cortisol in the intervention group. In the control group, however, the effect has a tendency to be positive from 8:30 a.m. to 10:30 a.m., and it is zero from 10:30 a.m. to 12:30 a.m., as can be seen in Table A2.

Changes in brain structure over the school year

Volumes of hippocampus and amygdala

Tables A3 and A4 present the descriptive statistics of the study variables for the analysis of changes in brain structure over the school year. In hippocampus and amygdala, maturation is conceived as an increase of volume, measured in *ml*, in this age group. The statistical analysis reveals a similar pattern of effects in the volumes of both hippocampus and the amygdala: The only credible effect that can be interpreted in causal terms (total effect) and that is backed by the design, is a medium-sized age effect in the volume of the hippocampus ($\beta = 0.40$, $sd = 0.22$), with older pupils displaying greater positive change from the beginning of the school year in fall t_1 to the end of the school year the following summer (t_2), that is greater maturation. In the amygdala, this age effect can only be seen as a trend, as are gender effects in

both hippocampus and amygdala, with girls seemingly having greater maturation. For a graphical display of the parameter estimates, see Figure 3. For the direct effects on the volume of the hippocampus at t_2, 11% of the variance could be explained by group, gender, cortisol and perceived autonomy support/choicefulness and only 3% in the amygdala. Information on model fit can be found in the supplementary material, section 2.2.

Thickness of rostral and caudal anterior cingulate cortices

In the ACC, maturation is conceived as a decrease in thickness in this age group, measured in *mm*. We can see a large direct effect of group in the rACC ($\beta = -0.77$, $sd = 0.35$), indicating greater decrease of thickness, that is maturation of the rACC, in the control group. This group effect is also visible as a trend in the change-score analysis (total effect in the mediation model). The analysis uncovers similar trends in the rostral and the caudal parts with respect for group and age. Perceived autonomy support/choicefulness is, with small to medium effect sizes, negatively associated with both rACC and cACC at t_2 while being controlled for the respective thickness at t_1. For the direct effects on the thickness of the rACC at t_2, 47% of the variance could be explained and 81% in the cACC. See Tables A5 and A6 for a summary of the parameter estimates and a graphical display of all parameters in Figure 3.

Post-hoc analyses revealed a small interaction effect between perceived autonomy support/choicefulness and group on the thickness of the rACC, which is credible at 85%: Choicefulness tends to have a greater effect on the maturation of the rACC in the intervention than in the control group. The parameter estimates for the post-hoc analysis can be found in Table A7. Information on the model, model fit and graphical displays of the post-hoc analysis can be found in the supplementary material, section 2.2.

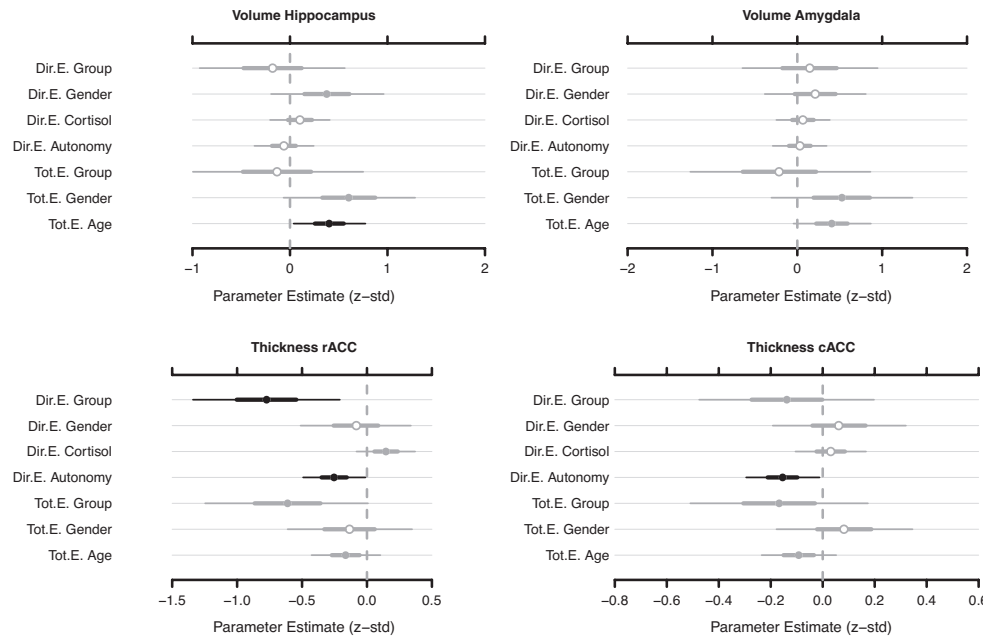

FIGURE 3 Maturation effects of the three brain regions, hippocampus, amygdala and anterior Cingulate cortex. Solid print intervals indicate effects different from zero in the 90% credible interval (CRI)

Auxiliary explanatory regressions

In order to understand the effects of choicefulness, cortisol and age on the development of the respective ROIs between the intervention and control groups, as well as between boys and girls, we included the respective paths into the models. We can see that averaged over the school year, the control group has significantly higher cortisol levels at the end of the school days, with a standardized regression coefficient $\beta = 0.76$, ($sd = 0.37$). Moreover, pupils in the control group are estimated to be significantly older, with a large standardized regression coefficient $\beta = 0.83$, ($sd = 0.37$), which translates to the six months in actual age difference mentioned above. There is also a trend that choicefulness is lower in the control group, averaged over the school year, and that girls have lower cortisol values at the end of the school days than boys (see Table A8).

Brain functioning under stress

Hippocampus and amygdala

Table A9 displays the descriptive statistics of the activation contrasts in the ROIs. The inferential analyses reveal that in the hippocampus, perceived autonomy support/choicefulness has a strong and credible effect on the activation in the *stress > rest* condition ($\beta = 1.19$, $sd = 0.58$), which has different directions in the two groups ($\beta = -0.70$, $sd = 0.39$): In the intervention group, higher choicefulness is positively associated with higher activation, whereas in the control group, the effect is reverse, which can also be seen as a trend in the amygdala. There, the pupils' age has the strongest effect, ($\beta = -0.46$, $sd = 0.26$): The younger the pupils, the more activation, which can also be seen as a trend in the hippocampus. In the hippocampus-model, 29% of the variance, and in the amygdala, 35% are explained in the *stress > rest* condition. If we look at the *stress > control* contrast, we can see that the biological predictor variable cortisol shows a similar pattern as the educational predictor variable choicefulness in the *stress > rest* condition: The effect is different in both groups, highly significant in the amygdala, ($\beta = 0.76$, $sd = 0.35$) and visible as a trend in the hippocampus. Pupils in the intervention group with lower cortisol values at the end of the school days have less brain activation in the amygdala under the *stress > control* condition in the MIST. Moreover, younger pupils show again higher activation, which is highly credible in the amygdala and visible as a trend in the hippocampus. In the hippocampus-model, 30% of the variance, and in the amygdala, 34% are explained in the *stress > rest* condition. Result Tables A10 and A11 summarize the respective parameter estimates, and Figure S4 displays the different directions of the effects in the two groups.

Anterior cingulate cortex

In the ACC, apart from age in the *stress > rest* condition, we cannot deem any activation effect credible with more than 80% credibility, in neither the rostral nor the caudal parts. We can see the same age-trend as in the hippocampus and the amygdala, as well as a small trend with girls exhibiting more activation than boys in the rACC. The interaction effect between group and autonomy, which we have seen in the *stress > rest* condition in the hippocampus and amygdala, can also be seen as a trend in the cACC in the *stress > rest* condition. Noteworthy is also the main effect for group in the cACC in the *stress > control* condition, credible in the 80% highest density interval (HDI), indicating less activation in the control group. In the ACC-models, 21–25% of the variance can be explained. Tables A12 and A13 summarize the respective parameter estimates.

DISCUSSION

To enhance knowledge of EOtC on pupils' stress-reactivity, we investigated if the degree of perceived autonomy support conceived as choicefulness during the teaching had any effect on the pupils' (1) biological stress regulation during the lessons, (2) their changes in brain structure over the school year and (3) their brain function under a stress test.

Biological stress regulation during classes

We believe that our findings tell a coherent story: Pupils are physically more active in the outdoor classes, and especially LPA in natural environments in the intervention group seems to have a stress-buffering effect and is associated with a decrease of the stress marker cortisol during the school day. This is in line with research on pupils' PA levels in EOtC (Schneller et al., 2017) and both the general narratives of stress coping within SDT (Ntoumanis et al., 2009) as well as of SRT (Schertz et al., 2021). However, the group effect for the overall decrease of cortisol between the intervention and the control groups lessens when the slopes are freely estimated and not fixed. In the two previous publications (Becker et al., 2019, Dettweiler, Becker et al., 2017), we only used random intercept models. Averaging over the slopes renders the mean slope significant, which can also be seen from the auxiliary regression in the maturation model (Table) where the average decrease of cortisol over the school days is averaged and compared between intervention and control groups.

Changes in brain structure

When we look at the maturation of the hippocampus, the amygdala and the ACC, we can see an expected age effect in all three brain ROIs, which is only credible in the hippocampus and visible as a trend in the amygdala and both parts of the ACC. In the latter, we can see credible statistical effects for perceived autonomy support/choicefulness, indicating that higher choicefulness over the school year is credibly associated with higher maturation of both parts of the ACC at the end of the school year. This finding is in line with Jiang et al. (2015) who connected proactive control to match anticipated needs with the rACC. However, given that choicefulness tends to be higher in the intervention group (Table A8), a finding that has been well established in EOtC research (Bølling et al., 2018, Dettweiler, Lauterbach et al., 2017), the statistically credible group effect with the control group showing higher maturation in the rACC, appears to be contra-intuitive. We would expect the opposite. Yet, as the post-hoc analysis shows, this group effect is based on four extreme cases, we define as >1.645 *sd* from the mean: three pupils in the intervention group (#8, +2.2 *sd* from mean; #19, −1.8 *sd* from mean; #23, +1.8 *sd* from mean) show extreme change in cortical thickness from t_1 to t_2, whereas one pupil (#39, −4.3 *sd* from mean) in the control group shows extreme decrease, see Table A7. It can be seen that #19 and #23 in the intervention group equal each other out, so that #8's + 2.2 *sd* in the intervention group and #39's − 4.3 *sd* create a rather large deviation from the mean across the groups. Based on non-extreme cases, the two groups show quite similar maturation in the rACC, as they do in the cACC. Thus, we would not consider this effect practically relevant.

More interesting is, however, the interaction effect of choicefulness and group on the thickness of the rACC at t_2, which indicates a greater effect on the maturation of the rACC in the intervention group: Although small and only credible in the 85% credible interval, it helps to explain the association of choicefulness in teaching and the structural changes in the rACC with its involvement in higher-level functions as decision-making (Bush et al., 2000), and adds another little piece to the puzzle of how learning in the outdoors might contribute to more robust brain structures and stress resilience.

Brain function under stress

A similar pattern can be seen in the analysis of the fMRI data in the *stress > rest* condition: The interaction effect between choicefulness and group reveals different directions of its association with brain activation under stress in the two teaching conditions, which is most credible in the hippocampus and visible as a trend in the cACC. Children in the intervention group with higher choicefulness display higher brain activation than their peers in the control group. Given the argumentation above, we would expect higher stress resilience in children with higher choicefulness and thus less brain activation. Yet, higher brain activity does not necessarily mean less stress resilience under a stress test. What we can see here is probably a stronger brain activation to the stress test among those children who might value making choices higher than their peers who report less choicefulness in class. It is not surprising that children who perceive themselves more self-determined appreciate making choices more than others and show a greater stress reaction under a stress test, which forces them into a rather rigid situation where the only choice they have would be to not take up the challenge. The matter of fact that with growing age we can detect less activation, as seen in all three brain ROIs, is according to our expectations.

If we look at the *stress > control* condition, it is noticeable that now the biological predictor variable shows the greatest effect: Cortisol levels at the end of the school days are very credibly associated with brain activation under stress in the amygdala. Children in the intervention group with lower cortisol values at the end of the school days have in fact less brain activation; the opposite is the case for children in the control group. Interestingly, it has also been shown that mindfulness training in middle school children can reduce self-perceived stress as well as amygdala reactivity to fearful faces (Bauer et al., 2019), which might suggest that EOtC and mindfulness probably address similar stress control networks in the brain.

Limitations

The main limiting factors in this study are certainly the small sample size, the unbalanced design resulting in a very small control group and the vulnerability of the analysis to extreme cases. As described above (Section 2.1), the research design had to be adjusted after the school had made last-minute changes at the beginning of the school year after we had already begun with the project. We tried to account for this flaw by meticulous statistical analyses and have applied a rather defensive line of argumentation. The readers are cautioned to interpret especially the structural brain data analyses with great diligence since averaging over the means does not necessarily represent nor explain individual trajectories very well. One final major limitation is the sampling frequency of the methods involved, which gives a rather coarse picture of the annual trajectories and which opens for many more stimuli that could possible produce the effects. After all, we still believe that this is an important contribution to understanding SRT, that is the physiological mechanisms behind nature's stress-buffering effect, and how EOtC can help to build stress resilience. Our findings justify further exploration and offer a structure to identify which areas of experimental design should be repeated with a larger sample size and with more measurement occasions.

CONCLUSION

In this study, we can show that the pupils in outdoor classes exhibit more efficient regulation of biological stress-reactivity and that lower cortisol levels are associated with LPA in natural environments. Structural MRI suggested that cerebral maturation effects could be best explained by age, however, that perceived autonomy support during the school year, conceived as choicefulness, had a positive direct effect on the maturation of the ACC, which appears to be stronger in the outdoor classes. Our results support the idea that autonomy supportive teaching fosters cerebral maturation and that EOtC taking place in natural green environments such as forests can have a positive effect on biological stress regulation systems. Further research will have to confirm our preliminary findings.

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AUTHOR CONTRIBUTIONS

Ulrich Dettweiler: Conceptualization; data curation; formal analysis; investigation; methodology; resources; software; validation; visualization; writing – original draft; writing – review and editing. **Martin Gerchen:** Conceptualization; methodology; software; validation; writing – original draft; writing – review and editing. **Christoph Mall:** Data curation; methodology; software; writing – original draft; writing – review and editing. **Perikles Simon:** Formal analysis; investigation; methodology; resources; software; supervision; writing – original draft; writing – review and editing. **Peter Kirsch:** Conceptualization; data curation; formal analysis; funding acquisition; investigation; methodology; project administration; resources; software; supervision; validation; writing – original draft; writing – review and editing.

CONFLICTS OF INTEREST

All authors declare no conflict of interest.

DATA AVAILABILITY STATEMENT

The data structure for the different analyses in this article is rather complex and stored in several data sets which can be obtained on request from the first author.

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SUPPORTING INFORMATION

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APPENDIX A

TABLE A1 Descriptive statistics of cortisol trajectories and light physical activity levels over the school days in the three seasons

	Fall		Spring		Summer	
	Intervention (*N* = 38)	Control (*N* = 11)	Intervention (*N* = 40)	Control (*N* = 11)	Intervention (*N* = 37)	Control (*N* = 11)
Cortisol (8:30), [µg/L]						
Mean (SD)	0.449 (0.268)	0.385 (0.162)	0.360 (0.235)	0.402 (0.243)	0.423 (0.185)	0.414 (0.134)
Median [Min, Max]	0.466 [−0.125, 1.07]	0.391 [0.0212, 0.613]	0.374 [−0.0915, 0.801]	0.416 [0.00860, 0.906]	0.403 [0.0128, 0.859]	0.413 [0.137, 0.603]
Cortisol (10:30), [µg/L]						
Mean (SD)	0.302 (0.195)	0.302 (0.192)	0.349 (0.208)	0.425 (0.198)	0.212 (0.214)	0.342 (0.148)
Median [Min, Max]	0.297 [−0.0706, 0.665]	0.316 [0, 0.640]	0.328 [−0.0969, 0.745]	0.399 [0.146, 0.850]	0.201 [−0.161, 0.946]	0.401 [0.0828, 0.498]
Cortisol (12:30), [µg/L]						
Mean (SD)	0.288 (0.236)	0.320 (0.131)	0.238 (0.186)	0.394 (0.123)	0.248 (0.198)	0.399 (0.172)
Median [Min, Max]	0.265 [−0.0706, 0.950]	0.294 [0.185, 0.585]	0.214 [0.00432, 0.841]	0.362 [0.243, 0.661]	0.242 [−0.208, 0.737]	0.394 [0.121, 0.663]
LPA (8:30–10:30), [%]						
Mean (SD)	26.3 (4.56)	24.1 (7.44)	22.3 (6.42)	26.0 (6.49)	28.4 (5.77)	27.9 (8.67)
Median [Min, Max]	26.7 [16.3, 34.6]	22.9 [12.1, 36.7]	22.3 [9.58, 36.1]	24.7 [15.2, 35.4]	28.8 [12.9, 39.6]	30.4 [12.5, 37.3]
LPA (10:30–12:30), [%]						
Mean (SD)	30.1 (7.73)	30.5 (8.66)	28.8 (6.35)	33.9 (7.27)	29.1 (5.88)	23.4 (9.70)
Median [Min, Max]	29.9 [14.2, 46.5]	28.0 [14.6, 41.3]	28.5 [18.5, 44.0]	33.5 [21.3, 48.5]	27.6 [19.4, 39.6]	25.0 [8.13, 37.3]

TABLE A2 Parameter estimates latent growth model

	Mean	SD	5%	20%	50%	80%	95%
Int. Group							
Intercept	0.19	0.29	−0.27	−0.06	0.19	0.44	0.67
Slope	−0.05	0.18	−0.35	−0.21	−0.05	0.11	0.25
Cortisol							
LPA 08:30–10:30	**−0.29**	**0.11**	**−0.46**	**−0.37**	**−0.29**	**−0.20**	**−0.11**
LPA 10:30–12:30	**−0.27**	**0.11**	**−0.46**	**−0.37**	**−0.27**	**−0.18**	**−0.09**
Control group							
Intercept	−0.05	0.42	−0.75	−0.41	−0.04	0.30	0.63
Slope	0.09	0.29	−0.37	−0.15	0.09	0.33	0.56
Season	0.07	0.14	−0.16	−0.05	0.08	0.20	0.31
Cortisol							
LPA 08:30–10:30	0.19	0.17	−0.09	0.05	0.19	0.33	0.47
LPA 10:30–12:30	−0.00	0.13	−0.21	−0.10	−0.00	0.10	0.20

Note: R^2 for Cortisol (Int. Group) at 8:30:=0.38, 10:30:=0.39, 12:30:=0.56.

R^2 for Cortisol (Control Group) at 8:30:=0.36, 10:30:=0.23, 12:30:=0.60.

PPP = 0.16, $\hat{R} < 1.05$ for all parameters.

ESS/*N* > 0.1 for LPA 08:30–10:30 and LPA 10:30–12:30.

All other parameters show high auto-correlations in the simulation and need to be interpreted with caution.

Intervals not overlapping zero are displayed in bold.

TABLE A3 Descriptive statistics of autonomy and cortisol averaged over the school year

	Intervention	Control
	(*N* = 30)	(*N* = 9)
Autonomy		
Mean (SD)	4.17 (0.485)	3.92 (0.770)
Median [Min, Max]	4.25 [3.25, 5.00]	3.88 [2.58, 4.75]
Cortisol		
Mean (SD)	−0.147 (0.153)	−0.0254 (0.159)
Median [Min, Max]	−0.172 [−0.522, 0.183]	−0.0524 [−0.274, 0.266]

TABLE A4 Descriptive statistics of structural MRI data

	Fall (t_1)		Summer (t_2)	
	Intervention	Control	Intervention	Control
	(*N* = 30)	(*N* = 9)	(*N* = 30)	(*N* = 9)
Volume Amygdala [ml]				
Mean (SD)	5.60 (0.407)	5.61 (0.441)	5.69 (0.625)	5.85 (1.01)
Median [Min, Max]	5.56 [4.85, 6.96]	5.44 [5.20, 6.58]	5.53 [4.91, 8.06]	5.51 [4.98, 8.29]
Volume Hippocampus [ml]				
Mean (SD)	7.19 (0.354)	7.04 (0.602)	7.28 (0.470)	7.27 (0.638)
Median [Min, Max]	7.14 [6.65, 8.25]	6.88 [6.24, 8.35]	7.26 [6.66, 8.42]	7.18 [6.46, 8.66]

(Continues)

TABLE A4 (Continued)

	Fall (t_1)		Summer (t_2)	
	Intervention ($N = 30$)	**Control** ($N = 9$)	**Intervention** ($N = 30$)	**Control** ($N = 9$)
Thickness rACC [mm]				
Mean (SD)	3.37 (0.201)	3.37 (0.200)	3.35 (0.196)	3.23 (0.217)
Median [Min, Max]	3.37 [2.73, 3.81]	3.38 [3.05, 3.63]	3.34 [3.05, 3.83]	3.29 [2.86, 3.55]
Thickness cACC [mm]				
Mean (SD)	3.06 (0.259)	3.24 (0.224)	3.06 (0.244)	3.19 (0.258)
Median [Min, Max]	3.02 [2.64, 3.68]	3.26 [2.84, 3.53]	3.02 [2.70, 3.67]	3.24 [2.63, 3.51]

TABLE A5 Parameter estimates maturation rACC

	Mean	SD	5%	20%	50%	80%	95%
Direct effects	$R^2 = 0.47$						
Group	**−0.77**	**0.35**	**−1.34**	**−1.22**	**−0.77**	**−0.34**	**−0.21**
Gender	−0.09	0.26	−0.51	−0.41	−0.08	0.24	0.34
Cortisol	0.15	0.14	−0.08	−0.03	0.15	0.32	0.37
Autonomy	**−0.25**	**0.15**	**−0.50**	**−0.49**	**−0.25**	**−0.07**	**−0.01**
Age	0.02	0.16	−0.25	−0.18	0.02	0.23	0.29
Total effects							
Group	−0.61	0.38	−1.25	**−1.10**	**−0.61**	**−0.13**	0.01
Gender	−0.13	0.29	−0.61	−0.50	−0.13	0.23	0.35
Age	−0.16	0.16	−0.43	−0.37	−0.17	0.04	0.10

Note: *PPP* = 0.35, $\hat{R} < 1.05$ for all parameters, $ESS/N > 0.1$ for all parameters.
Intervals not overlapping zero are displayed in bold.

TABLE A6 Parameter estimates maturation cACC

	Mean	SD	5%	20%	50%	80%	95%
Direct effects	$R^2 = 0.81$						
Group	−0.14	0.21	−0.48	−0.40	−0.14	0.12	0.20
Gender	0.06	0.16	−0.19	−0.13	0.06	0.26	0.32
Cortisol	0.03	0.08	−0.11	−0.07	0.03	0.14	0.17
Autonomy	**−0.15**	**0.07**	**−0.30**	**−0.26**	**−0.15**	**−0.05**	**−0.01**
Age	−0.06	0.10	−0.22	−0.18	−0.06	0.06	0.01
Total effects							
Group	−0.17	0.21	−0.51	−0.43	−0.17	0.10	0.17
Gender	0.08	0.16	−0.18	−0.12	0.08	0.29	0.35
Age	−0.09	0.09	−0.24	−0.20	−0.09	0.02	0.05

Note: *PPP* = 0.37, $\hat{R} < 1.05$ for all parameters, $ESS/N > 0.1$ for all parameters.
Intervals not overlapping zero are displayed in bold.

TABLE A7 Extreme changes in thickness rACC from t_1 to t_2

Pupil ID	Group	Δ*rACC*	Deviation from mean
#8	Intervention	0.39	2.2 SD
#19	Intervention	−0.30	−1.8 SD
#23	Intervention	0.32	1.8 SD
#39	Control	−0.75	−4.3 SD

TABLE A8 Auxiliary regressions in the maturation model

	Mean	SD	5%	20%	50%	80%	95%
Autonomy	$R^2 = 0.05$						
Group	−0.45	0.39	−1.07	**−0.77**	**−0.45**	**−0.13**	0.19
Gender	0.25	0.33	−0.29	−0.02	0.25	0.52	0.79
Cortisol	$R^2 = 0.11$						
Group	**0.76**	**0.37**	**0.16**	**0.46**	**0.76**	**1.07**	**1.37**
Gender	−0.32	0.31	−0.83	**−0.58**	**−0.32**	**−0.06**	0.20
Age	$R^2 = 0.11$						
Group	**0.83**	**0.37**	**0.22**	**0.52**	**0.83**	**1.13**	**1.44**
Gender	−0.04	0.32	−0.55	−0.30	−0.04	0.22	0.48
rACC t_2,							
Autonomy:Group	0.14	0.10	−0.03	**0.05**	**0.14**	**0.21**	0.29

Note: $PPP = 0.55$, $\hat{R} < 1.05$ for all parameters, $ESS/N > 0.1$ for all parameters.
Intervals not overlapping zero are displayed in bold.

TABLE A9 Descriptive statistics of activation contrasts

	Stress > control		Stress > rest	
	Intervention ($N = 24$)	Control ($N = 8$)	Intervention ($N = 24$)	Control ($N = 8$)
Amygdala				
Mean (SD)	0.126 (0.728)	−0.0347 (0.615)	−0.159 (0.586)	0.0154 (0.490)
Median [Min, Max]	0.198 [−1.37, 1.90]	0.0809 [−1.16, 0.653]	−0.167 [−1.74, 1.12]	0.0984 [−0.726, 0.672]
Hippocampus				
Mean (SD)	0.156 (0.445)	0.0588 (0.265)	−0.0463 (0.502)	0.102 (0.297)
Median [Min, Max]	0.151 [−1.20, 1.04]	0.135 [−0.444, 0.294]	0.00435 [−1.96, 0.819]	0.215 [−0.417, 0.417]
rACC				
Mean (SD)	0.520 (1.04)	−0.220 (0.697)	0.0844 (0.897)	−0.0757 (0.493)
Median [Min, Max]	0.436 [−0.966, 2.85]	−0.294 [−0.978, 0.792]	0.0994 [−1.34, 2.55]	−0.257 [−0.597, 0.780]
cACC				
Mean (SD)	0.333 (0.894)	−0.279 (0.584)	0.671 (0.707)	0.350 (0.488)
Median [Min, Max]	0.0142 [−0.842, 2.73]	−0.360 [−1.21, 0.589]	0.477 [−0.386, 2.68]	0.370 [−0.217, 0.920]

TABLE A10 Parameter estimates activation hippocampus

	Median	MAD	5%	20%	50%	80%	95%
Contrast Stress>Rest, $R^2 = 0.29$							
Group	0.24	0.52	−0.59	−0.26	0.24	0.61	1.14
Age	−0.22	0.22	−0.58	**−0.39**	**−0.22**	**−0.02**	0.15
Gender	0.20	0.34	−0.37	−0.09	0.20	0.48	0.79
Cortisol	−0.06	0.59	−1.04	−0.6	−0.06	0.40	0.97
Autonomy	**1.19**	**0.58**	**0.21**	**0.72**	**1.19**	**1.70**	**2.16**
Autonomy:Group	**−0.70**	**0.39**	**−1.36**	**−1.07**	**−0.7**	**−0.41**	**−0.05**

TABLE A10 (Continued)

	Median	MAD	5%	20%	50%	80%	95%
Cortisol:Group	0.04	0.46	−0.72	−0.28	0.04	0.51	0.84
Contrast Stress>Control, $R^2 = 0.27$							
Group	−0.11	0.25	−0.52	−0.31	−0.11	0.12	0.30
Age	−0.16	0.11	−0.34	**−0.25**	**−0.16**	**−0.06**	0.03
Gender	0.13	0.16	−0.17	0.00	0.13	0.27	0.39
Cortisol	**−0.33**	**0.28**	**−0.83**	**−0.58**	**−0.33**	**−0.10**	**0.14**
Autonomy	0.07	0.28	−0.42	−0.16	0.07	0.32	0.51
Autonomy:Group	−0.07	0.18	−0.37	−0.22	−0.07	0.08	0.24
Cortisol:Group	**0.25**	**0.21**	**−0.11**	**0.08**	**0.25**	**0.44**	**0.61**

Note: $\hat{R} < 1.05$ for all parameters, $ESS/N > 0.1$ for all parameters.

Since a skew-normal likelihood function was used to estimate the parameters, the median is given as the centrality measure and the mean absolute deviation (MAD) is used as the dispersion statistics. For more information see supplement.

Intervals not overlapping zero are displayed in bold.

TABLE A11 Parameter estimates activation amygdala

	Median	MAD	5%	20%	50%	80%	95%
Contrast Stress>Rest, $R^2 = 0.35$							
Group	0.34	0.59	−0.61	−0.15	0.34	0.84	1.31
Age	**−0.46**	**0.26**	**−0.85**	**−0.68**	**−0.46**	**−0.25**	**−0.04**
Gender	0.14	0.38	−0.50	−0.16	0.14	0.48	0.78
Cortisol	−0.65	0.70	−1.80	−1.23	−0.65	−0.05	0.55
Autonomy	0.72	0.68	−0.38	**0.18**	**0.72**	**1.33**	1.90
Autonomy:Group	−0.53	0.43	−1.24	**−0.89**	**−0.53**	**−0.16**	0.22
Cortisol:Group	0.49	0.51	−0.36	**0.08**	**0.49**	**0.95**	1.36
Contrast Stress>Control, $R^2 = 0.34$							
Group	−0.13	0.39	−0.80	−0.40	−0.13	0.25	0.47
Age	**−0.33**	**0.14**	**−0.56**	**−0.46**	**−0.33**	**−0.22**	**−0.08**
Gender	0.07	0.24	−0.33	−0.11	0.07	0.29	0.48
Cortisol	**−1.06**	**0.5**	**−1.86**	**−1.49**	**−1.06**	**−0.65**	**−0.21**
Autonomy	−0.36	0.45	−1.09	−0.73	−0.36	0.03	0.43
Autonomy:Group	0.09	0.30	−0.40	−0.16	0.09	0.33	0.59
Cortisol:Group	**0.76**	**0.35**	**0.14**	**0.46**	**0.76**	**1.05**	**1.33**

Note: $\hat{R} < 1.05$ for all parameters, $ESS/N > 0.1$ for all parameters.

Since a skew-normal likelihood function was used to estimate the parameters, the median is given as the centrality measure and the mean absolute deviation (MAD) is used as the dispersion statistics. For more information see supplement.

Intervals not overlapping zero are displayed in bold.

TABLE A12 Parameter estimates activation rACC

	Median	MAD	5%	20%	50%	80%	95%
Contrast Stress>Rest, $R^2 = 0.25$							
Group	0.40	0.51	−0.49	0.02	0.40	0.86	1.23
Age	**−0.30**	**0.18**	**−0.62**	**−0.46**	**−0.30**	**−0.15**	**0.00**
Gender	0.55	0.35	−0.08	**0.28**	**0.55**	**0.87**	1.14
Cortisol	0.11	0.63	−0.97	−0.45	0.11	0.60	1.14
Autonomy	0.45	0.57	−0.52	−0.06	0.45	0.90	1.44
Autonomy:Group	−0.13	0.38	−0.79	−0.48	−0.13	0.15	0.49
Cortisol:Group	−0.06	0.45	−0.82	−0.44	−0.06	0.32	0.73
Contrast Stress>Control, $R^2 = 0.22$							
Group	−0.53	0.57	−1.49	**−0.99**	**−0.53**	**−0.02**	0.45
Age	−0.14	0.21	−0.51	−0.31	−0.14	0.05	0.21
Gender	0.04	0.40	−0.64	−0.27	0.04	0.40	0.69
Cortisol	0.06	0.68	−1.10	−0.50	0.06	0.65	1.18
Autonomy	−0.08	0.64	−1.20	−0.63	−0.08	0.45	0.97
Autonomy:Group	0.11	0.41	−0.58	−0.21	0.11	0.47	0.82
Cortisol:Group	0.03	0.50	−0.83	−0.39	0.03	0.44	0.85

Note: $\hat{R} < 1.05$ for all parameters. $ESS/N > 0.1$ for all parameters.

Since a skew-normal likelihood function was used to estimate the parameters, the median is given as the centrality measure and the mean absolute deviation (MAD) is used as the dispersion statistics. For more information see supplement.

Intervals not overlapping zero are displayed in bold.

TABLE A13 Parameter estimates activation cACC

	Median	MAD	5%	20%	50%	80%	95%
Contrast Stress>Rest, $R^2 = 0.25$							
Group	−0.32	0.53	−1.22	−0.71	−0.32	0.19	0.57
Age	−0.23	0.19	−0.54	−0.38	−0.23	−0.06	0.1
Gender	−0.04	0.35	−0.63	−0.34	−0.04	0.25	0.57
Cortisol	−0.13	0.69	−1.29	−0.69	−0.13	0.47	1.01
Autonomy	0.93	0.65	−0.13	**0.37**	**0.93**	**1.46**	2.03
Autonomy:Group	−0.54	0.43	−1.28	**−0.88**	**−0.54**	**−0.16**	0.16
Cortisol:Group	0.15	0.5	−0.71	−0.25	0.15	0.6	0.98
Contrast Stress>Control, $R^2 = 0.21$							
Group	−0.66	0.47	−1.44	**−1.05**	**−0.66**	**−0.26**	0.15
Age	0.02	0.17	−0.28	−0.11	0.02	0.17	0.3
Gender	0.07	0.33	−0.52	−0.18	0.07	0.38	0.6
Cortisol	−0.03	0.55	−0.98	−0.49	−0.03	0.43	0.9
Autonomy	0.16	0.53	−0.75	−0.34	0.16	0.57	1.09
Autonomy:Group	−0.12	0.35	−0.72	−0.42	−0.12	0.18	0.48
Cortisol:Group	0.07	0.41	−0.62	−0.32	0.07	0.37	0.8

Note: $\hat{R} < 1.05$ for all parameters. $ESS/N > 0.1$ for all parameters.

Since a skew-normal likelihood function was used to estimate the parameters, the median is given as the centrality measure and the mean absolute deviation (MAD) is used as the dispersion statistics. For more information see supplement.

Intervals not overlapping zero are displayed in bold.