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Post-error adjustments and ADHD symptoms in adults: The effect of laterality and state regulation

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ABSTRACT

Evidence is accumulating that individuals with Attention-Deficit/Hyperactivity Disorder (ADHD) do not adjust their responses after committing errors. Post-error response adjustments are taken to reflect, among others, error monitoring that is essential for learning, flexible behavioural adaptation, and achieving future goals. Many behavioural studies have suggested that atypical lateral brain functions and difficulties in allocating effort to protect performance against stressors (i.e., state regulation) are key factors in ADHD. Whether these factors contribute to the absence of post-error response adjustments in ADHD is unknown. The aim of the present study is to investigate the contribution of the left and right hemispheres and the deficiency in effort allocation to deviant post-error processing in adults with high ADHD symptoms. From a pool of 87 university students, two groups were formed: a group with higher ($n = 30$) and a group with lower ($n = 26$) scores on the ADHD index subscale of the Conners' Adult ADHD Rating Scales. The groups performed a lateralized lexical decision task with a fast and slower stimulus presentation rate. Post-error slowing and post-error response accuracy to stimuli presented in the left and right visual field were measured in each stimulus presentation rate. Results indicated that subjects with the lower ADHD scores slowed down and improved their response accuracy after errors, especially when stimuli were presented in the right visual field at the slower rate. In contrast, subjects with the higher ADHD scores showed no post-error adjustments. Results suggest that during lexical decision performance, impaired error processing in adults with ADHD is associated with affected ability of the left hemisphere to compensate for errors, especially when extra effort allocation is needed to meet task demands.

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1. Introduction

Attention-deficit/hyperactivity disorder (DSM 5) is a common childhood disorder that in 60–70% of cases persists into adulthood (de Zwaan et al., 2012; see also meta-analysis of Faraone, Biederman, & Mick, 2006). To study the nature of the cognitive impairments and performance alterations in the disorder, many studies have used reaction time tasks. The key finding is that individuals with ADHD are slower and more variable in their responses compared to control groups (Hervey, Epstein, & Curry, 2004; Kofler et al., 2013). In addition, individuals from the ADHD groups commit more errors and do not slow down their performance after an error, whilst control groups do. The presence of post-error slowing in control groups and its absence in ADHD groups has been

reported in a variety of tasks such as the Go/No-Go task, the choice reaction time task, the stop signal task and the flanker task (for a meta-analysis see, Balogh & Czobor, 2014).

There is an ongoing debate over the mechanisms behind post-error slowing. The phenomenon could be attributed to an adaptive mechanism that induces a more cautious response to prevent making another error on a subsequent trial (Gehring & Fencsik, 2001; Jentsch & Dudshig, 2009; Ridderinkhof, Ullsperger, Crone, & Nieuwenhuis, 2004). In this vein, post-error slowing should be associated with an increase in post-error response accuracy (Danielmeier, Eichele, Forstmann, Tittgemeyer, & Ullsperger, 2011; Debener et al., 2005; Hajcak, McDonald, & Simons, 2003). However, some studies failed to find this association (Danielmeier & Ullsperger, 2011; Hajcak & Simons, 2008; King, Korb, von Cramon, & Ullsperger, 2010), and some even reported decreased post-error response accuracy together with post-error slowing (Fiehler, Ullsperger, & Von Cramon, 2005; Rabbitt & Rodgers, 1977). The latter finding supports another explanation

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that post-error slowing results from the persistence of a defective process that caused an error on the previous trial (Gehring & Fencsik, 2001; Gehring, Goss, Coles, Meyer, & Donchin, 1993). A third explanation is that post-error slowing can arise from an attentional lapse due to involuntary shifting of attention towards an error (as an infrequent event), i.e. the orienting account (Dutilh, Vandekerckhove, et al., 2012; Notebaert et al., 2009). Kerns et al. (2004) and Ridderinkhof et al. (2004) have summarized evidence that post-error slowing can also rely on the interplay of conflict monitoring and cognitive control.

In sum, the mechanism behind post-error slowing is still unclear. The same holds for its neural basis. For instance, the two error related brain potentials, the Error-Related Negativity (ERN) and Error-Related Positivity (Pe) are considered in some studies to reflect respectively the automatic mechanism of error detection and conscious awareness of error making (Hajcak et al., 2003; Herrmann, Römmler, Ehlis, Heidrich, & Fallgatter, 2004; Nieuwenhuis, Ridderinkhof, Blom, Band, & Kok, 2001). However, in other studies the two potentials are considered to reflect monitoring conflict responses instead of error processing (Barch, Braver, Sabb, & Noll, 2000; Carter et al., 1998; Gehring & Fencsik, 2001; Scheffers, Humphrey, Stanny, Kramer, & Coles, 1999; Strozyk & Jentzsch, 2012; van Veen & Carter, 2002).

Concerning the brain areas involved in error making and related response adjustments, it might be concluded at best that two distinct neural brain regions are involved in error processing (Kerns et al., 2004; Ridderinkhof et al., 2004), the Anterior Cingulate Cortex (ACC) and the posterior medial frontal cortex. The regions are respectively linked with error detection (Garavan, Ross, Kaufman, & Stein, 2003; Lütcke & Frahm, 2008) and post-error response adjustments (Danielmeier et al., 2011). Whether the two hemispheres have a differential involvement in error processing is still inconclusive, albeit most neuro-imaging and EEG evidence supports the idea that the left hemisphere is the most promising candidate to subserve error related processing (Hochman, Eviatar, Breznitz, Shaul, & Nevat, 2009; King et al., 2010; Lütcke & Frahm, 2008; Swick & Turken, 2002; Westlye, Walhovd, Bjørnerud, Due-Tønnessen, & Fjell, 2009).

Behavioural studies focusing on post-error adjustments and brain laterality suggest that there are two independent parallel hemispheric strategies and that the right hemisphere uses the most appropriate compensatory strategy that yields an enhanced task performance. This interpretation is based on performance on lexical decision tasks with visual hemi-field stimulation. Zaidel and colleagues have argued that lateralized lexical decision task can provide a “direct access model”, referring to the fact that stimuli presented to the left visual field (LVF) are initially processed by the right hemisphere, and those presented to the right visual field (RVF) are initially processed by the left hemisphere (Iacoboni, Rayman, & Zaidel, 1997; Kaplan & Zaidel, 2001; Narr, Green, Capetillo-Cunliffe, Toga, & Zaidel, 2003; Zaidel, 1987; Zaidel, Clarke, & Suyenobu, 1990). In these studies, either the effect of an error on a subsequent performance or the effect of feedback on performance has been tested. Most of the studies reported a post-error slowing for RVF stimuli and improved post-error response accuracy for LVF stimuli, especially after a negative feedback. An improvement in post-error response accuracy in the RVF was considered to reflect a right hemispheric dominance for error correction.

The present study aims to address a gap in the literature exploring the role of brain laterality in post-error adjustments in subjects with high and low levels of self-reported ADHD. Many behavioural studies have reported atypical brain laterality in ADHD on a variety of lateralization tasks including a line bisection test, the dichotic listening task, Posner's cueing task, and the lexical decision task (Carter, Krener, Chaderjian, Northcutt, & Wolfe, 1995; Hale,

Zaidel, McGough, Phillips, & McCracken, 2006; Hale et al., 2005; Song & Hakoda, 2012). Some researchers have concluded that atypical brain laterality might be seen as a key component of cognitive impairments in ADHD (Hale et al., 2009). Although more research is still needed to answer the question whether the left or the right hemisphere is compromised, most evidence is in favour of a right hemisphere dysfunction (Hale et al., 2008; Mohamed, Börger, Geuze, & van Der Meere, 2015a; Sandson, Bachna, & Morin, 2000). In this vein, one might hypothesize that lateralized deficits in ADHD may contribute to some extent to their deviant post-error processing.

A second aim of the present study is to test whether impaired state regulation is another contributing factor to the absence of post-error slowing in subjects with ADHD. Using the state regulation model, evidence is mounting that poor task performance including error processing is associated with difficulty in applying sufficient effort to protect performance against stressors such as a short versus longer inter-stimulus interval, reward versus punishment, and presence versus absence of the experimenter during testing participants (for reviews see, Sonuga-Barke, Wiersma, van der Meere, & Roeyers, 2010; van der Meere, 2005; van der Meere, Börger, & Wiersma, 2010). In ADHD studies, the most popular stressor to manipulate effort allocation is to vary the inter-stimulus interval from short to long. Short and long inter-stimulus intervals (i.e., fast and slow presentation rate of stimuli) were used to induce high and low motor activation state (a tonic readiness for giving a motor response during response preparation phase). Although the exact operational definition of the inter-stimulus interval that constitutes stress are still lacking and vary among studies (Metin et al., 2016; for meta-analysis see, Metin, Roeyers, Wiersma, van der Meere, & Sonuga-Barke, 2012), a robust finding that reaction time performances of groups with ADHD declines during longer inter-stimulus intervals compared to short intervals has been reported. That is to say, correct responses are becoming slower and more variable. The finding has been interpreted in terms of dysregulated cognitive-energetic resources that results a failure to modulate the low motor activation state of the subjects at slower inter-stimulus intervals (van der Meere, 2005; van der Meere et al., 2010).

Balogh and Czobor (2014) were the first to link the effect of inter-stimulus interval to error processing in ADHD. They reported that error-processing studies in ADHD used different inter-stimulus intervals. To explore the effect of inter-stimulus intervals, Balogh and colleague carried out a meta-analysis and reported that increased post-error slowing is associated with longer inter-stimulus intervals in the control groups, while post-error slowing was markedly diminished in subjects with ADHD. The finding could be explained in terms of less effort allocation in the ADHD groups to adjust performance after error making. This explanation calls for a direct manipulation of the inter-stimulus interval to explore whether post-error response adjustments are similar between ADHD and control groups during a fast stimulus presentation rate, but decreases in the ADHD group when stimuli are presented in a slower rate.

Another possibility is that deviant post-error processing in ADHD could be shaped by an interplay between atypical lateral brain functions and difficulties in regulating the motor activation. Many studies have suggested that the left hemisphere is specialized in regulating the motor activation state via dopaminergic neurons (Declerck, De Brabander, & Boone, 2004; Tucker & Williamson, 1984). Consequently, the left hemisphere has to become more active especially during the slower stimulus presentation rate to maintain an optimal task performance. Given the fact that ADHD groups have a problem in regulating their motor activation state during the slower rates, poor task performance including error

processing might be associated with affected left hemisphere-functioning.

To investigate the contribution of the left and right hemispheres and effort allocation to post-error adjustments, we combined two experimental manipulations in a lexical decision task: visual hemi-field stimulation tapping brain laterality (Gold, Powell, Xuan, Jiang, & Hardy, 2007; Hunter & Brysbaert, 2008) and duration of inter-stimulus interval. The task was performed by two groups of adults with lower and higher scores on the ADHD Index scale of the Conners' Adult ADHD Rating Scales (CAARS; Conners, Erhardt, & Sparrow, 1999). The sample was derived from a normal population. Our selection strategy is based on the so-called psychometric trait approach. The approach assumes that clinical ADHD represents the extreme end of a quantitative trait which is normally distributed in the general population. Much empirical support for the approach comes from studies showing that self-reported ADHD symptoms are normally distributed and linked with neurocognitive (Crosbie et al., 2013; Mohamed, Börger, Geuze, & van der Meere, 2015b; Polner, Aichert, Macare, Costa, & Ettinger, 2015) and genetic factors (Larsson, Anckarsater, Råstam, Chang, & Lichtenstein, 2012; Nikolas & Burt, 2010). The approach provides more insight into potential endophenotypes of ADHD (Polner et al., 2015). More interestingly, self-report inattentive (ADHD) symptoms have proven to be associated with compromised error processing: normal subjects with higher symptoms had reduced amplitudes of error-positivity related potential indicating less awareness of error making, less effortful adjustments after noticing an error, and/or absence of the motivational significance of the error (Herrmann et al., 2009).

2. Method

2.1. Participants

Eighty-seven native Dutch or German students from the University of Groningen were recruited. Based on their scores on the ADHD Index scale of the Conners' Adult ADHD Rating Scales, participants with scores in the first tertile were classified as a group with lower ADHD symptoms ($n = 26$) and those with scores in the third tertile were classified as a group with high ADHD symptoms ($n = 30$). Both groups were right-handed as they scored above 40 on the Edinburgh Handedness Inventory (Oldfield, 1971). All participants reported normal or corrected to normal vision, and no use of medication at least 24 h before their participation. Nineteen participants of the high ADHD symptoms group reported a DSM-ADHD diagnosis. Table 1 presents characteristics of both groups.

The Ethics Committee Psychology of the University of Groningen approved the study. Participants also gave written informed consent for their participation.

2.2. Materials and apparatus

2.2.1. Questionnaires

The ADHD Index scale of the CAARS (Conners et al., 1999) was used to measure self-reported ADHD symptoms. The scale provides a method to identify adults who are likely to be diagnosed with ADHD and has been considered the most reliable and valid scale to measure the overall ADHD symptomatology (Conners et al., 1999; Hudziak, Derks, Althoff, Rettew, & Boomsma, 2005). The ADHD Index scale consists of 12 items covering the four areas of impairments (inattention, hyperactivity, impulsivity, and problems with self-concept).

To confirm that the group with high ADHD symptoms had more clinical impairments in daily life activities, the Weiss Functional Impairment Rating Scale (WFIRS; NACE, 2014; Weiss, 2010) and Executive Function Index Scale (EFI; Spinella, 2005) were applied. The WFIRS consisted of 70 items measuring adult's function across seven domains: family, work, learning and school/college, life skills, self-concept, social functioning, and risk taking. The EFI consists of 27 items distributed over five subscales: Motivational Drive, Organization, Impulse Control, Empathy, and Strategic Planning. For the WFIRS, higher scores indicate more functional impairments and for the EFI, lower scores indicate poor frontal lobe/executive functioning.

All scales evidenced adequate reliability and validity to estimate ADHD symptomatology, functional impairments, and executive functions (Adler et al., 2008; Erhardt, Epstein, Conners, Parker, & Sitarenios, 1999; Kooij et al., 2008; Miley & Spinella, 2006; Spinella, 2005; Weiss, 2010).

2.2.2. A lateralized lexical decision task

The task was conducted on a laptop computer using E-Prime software version 2.0. The monitor was antiglare with a resolution of 1024×768 pixels and a refresh rate of 60 Hz. Targets and distractors were horizontal letter strings presented bilaterally in lower-case and black in colour on a silver background for 150 ms. All letters were displayed in Arial font with point size of 14. The target letter string was underlined and presented to either the LVF or the RVF, while the distractor (non-underlined letter string) was presented to the opposite visual field. The number of letters for the target and the distractor were equal and ranged from 3 to 5 letters.

The participants were instructed to indicate whether the target was a word or a non-word. The task was presented in Dutch

Table 1
Characteristics of the study sample.

Variables	High ADHD Group	Low ADHD Group
Number of participants (gender, language)	30 (16 females, 17 Dutch)	26 (15 females, 10 Dutch)
Age	$M = 23.33$, $SD = 3.37$ (Min:Max = 19:31)	$M = 20.30$, $SD = 1.46$ (Min:Max = 18:24) two subjects are younger than 19 years
Reporting a DSM-ADHD diagnosis (time of diagnosis)	19 participants (15 in adulthood, 4 in childhood)	None of the participants
Reporting other disorders with DSM diagnosis	Two reported Anxiety, 4 reported both Anxiety and Depression, 3 reported Depression, and two participants had reading disorders during their childhood	None of the participants
T-score on the ADHD Index scale	$M = 65.50$, $SD = 7.73$ (Min:Max = 55:85)	$M = 40.69$, $SD = 3.95$ (Min:Max = 32:45)
Scores on the Edinburgh Handedness Inventory	$M = 79.09$, $SD = 19.41$ (Min:Max = 42:100)	$M = 84.77$, $SD = 19.34$ (Min:Max = 41:100)
Scores on the EFI	$M = 85.83$, $SD = 11.17$ (Min:Max = 52:104)	$M = 103.32$, $SD = 11.13$ (Min:Max = 85:143)
Scores on the WFIRS	$M = 7.35$, $SD = 3.15$ (Min:Max = 1.18:13.76)	$M = 2.53$, $SD = 1.62$ (Min:Max = 0.44:7.97)

Note: EFI = Executive Function Index scale; WFIRS = Weiss Functional Impairment Rating Scale; High ADHD Group = Participants with scores fall in the third tertile of ADHD index scores; Low ADHD Group = Participants with scores fall in the first tertile of ADHD index scores.

(for 27 participants) and in German (for 29 participants) matching the participants' mother language. The innermost edge of each letter-string was located at 1.23° to the left or the right side of a central fixation cross-displayed in Arial font with 12-point size. The target was presented equally frequently in both visual fields in a semi random order. The presentation ratio of target word and target non-word was equal in each visual field. For words, half had a high frequency of accuracies (greater than 100 per million) and the other half had a low frequency (less than 50 per million) in written and spoken language. High and low frequency words were derived from two databases: CELEX (Baayen, Piepenbrock, & Gulikers, 1995) and SUBTLEX (Brysbaert & New, 2010; Brysbaert et al., 2011). Non-words were generated using Wuggy software (Keuleers & Brysbaert, 2010).

The task had two conditions: a condition with a short inter-stimulus interval of 2000 ms (i.e., fast presentation rate condition) that had 384 trials and another with a longer inter-stimulus interval of 4200 ms (i.e., slower presentation rate) with 192 trials. Inter-stimulus interval was defined as the duration from the offset of one stimulus to the onset of the next stimulus. The two conditions combined lasted approximately 30 min.

The lexical decision task has been validated to explore the independent ability of each hemisphere to post-error response adjustment. Post-error response adjustments were measured as the differences between post-correct trials and post-error trials. Post-error response adjustments in left and right visual field were taken to reflect hemispheric asymmetry in error processing (Hochman & Eviatar, 2004, 2006; Iacoboni et al., 1997; Kaplan & Zaidel, 2001; Narr et al., 2003; Zaidel, 1987; Zaidel et al., 1990). Post-error response adjustments during fast and slower stimulus presentation rate were taken to reflect the effect of effort allocation/state regulation on error processing.

2.3. Procedure

The participants were first asked to fill in the questionnaires and to provide information about their use of medication, having a diagnosis of ADHD, mood disorders, learning disabilities, and/or visual problems. Thereafter, the participants performed the computerized lexical decision task sitting at a table in a dimly lit room. They placed their chins on a chin-rest positioned at 57 cm from the monitor. A response box with two buttons was placed between the monitor and the chin rest. The participants were instructed to press button '1' with their index fingers if the target was a word and to press button '2' with their middle fingers if the target was a non-word. Trials were not followed by feedback. Responses were made with the right hand in half of the trials. In the second half of the trials the left hand was used. The order of the responding hand and presentation rate conditions were counterbalanced. It was emphasized that participants should keep their gaze on the central fixation cross, i.e. without turning their gaze away when stimuli appeared. They were instructed to react as fast and accurately as possible. Before running the task, practice trials were given until seven out of ten consecutive trials were correctly answered.

2.4. Data analysis

Differences between the two groups in scores on the Edinburgh Handedness Inventory (Oldfield, 1971), the ADHD index of the CAARS, the WFIRS, and the EFI were tested. To study the characteristics of errors in both groups, differences between the groups in the amount of errors and differences between errors and correct responses in mean Reaction Times (RT) in each group were tested.

Mean RT of correct responses following errors and that following correct trials were calculated apart for the LVF and RVF in each

stimulus presentation rate. The contribution of the left hemisphere to post-error processing was investigated by testing whether errors to RVF stimuli led to slower performance and/or increased response accuracy on the subsequent RVF trials (RVF-RVF trial sequences). In the same manner, the right hemisphere's post-error processing was investigated (the effect of errors in the LVF on the subsequent LVF trials: LVF-LVF trial sequences). A repeated measure analysis of variance was performed on mean RT. The within-subjects factors were *correctness* (performance after correct trials or performance after errors), *visual field* (LVF-LVF or RVF-RVF trial sequences), and *stimulus presentation rate* (fast or slower rate). To test the group differences in the contribution of each hemisphere and state regulation, a between-subjects factor of *group* (higher or lower ADHD scores) was added to the analysis was added to the analysis.

Using a more precise measurement of post-error slowing proposed by Dutilh, van Ravenzwaaij, et al. (2012), the effect of state regulation (i.e., stimulus presentation rate) on error processing was tested. For each presentation rate, post-error slowing was calculated as the difference in correct RT between trials after ($E + 1$) and before an error ($E - 1$) for trial sequences where two correct trials preceded an error. The effect of brain laterality was not tested because there were not enough trial sequences (four trials in a row) presented to the same visual field. The mean number of errors was respectively 74 and 32 for the fast and the slower presentation rate. A repeated measure analysis of variance was performed on the size of post-error slowing. The within subject factor was *stimulus presentation rate* (fast or slower rate). Group differences in the effects of the presentation rate on post-error slowing were tested by adding a between-subject factor of *group* (higher or lower ADHD scores) to the analysis.

Relative measures of correct responses following errors and that following correct trials were calculated per visual field and presentation rate. In each presentation rate, we applied the following equation to estimate post-error accuracy in the LVF: [(number of correct LVF-trials following LVF-errors/total number of trials following LVF-errors) $\times 100$]. Similarly, we estimated post-error accuracy in the RVF. Repeated measure analysis of variance was performed on the relative measures of correct responses using the same within- and between-subject factors as in RT analysis.

Errors proved to be normally distributed in the fast and the slower presentation rate, as indicated by Shapiro-Wilk test ($S-W = 0.976$, $df = 54$, $p = 0.34$, for the fast rate and $S-W = 0.979$, $df = 54$, $p = 0.47$ for the slower rate). The mean number of RVF-errors followed by RVF-trials and the mean number of LVF-errors followed by LVF-trials were respectively 15 and 17 in the fast rate and 8 and 9 in the slower rate. In the slower presentation rate, three participants had a missing value in one of the visual field conditions. The missing value was replaced by the mean scores (RT and correct responses) of the participant.

To test whether the responding hand affects post-error adjustments, repeated measure analysis of variance was performed for LVF-LVF, RVF-RVF trial sequences only. The within-subjects factors were *correctness* (performance after correct trials or performance after errors), *Responding hand* (right or left hand), *visual field* (LVF-LVF or RVF-RVF trial sequences), and *stimulus presentation rate* (fast or slower rate). The between-subjects factor was *group* (higher or lower ADHD scores).

3. Results

3.1. Groups differences in handedness and questionnaires

The two groups did not differ in handedness scores ($t(54) = -1.094$, $p = 0.279$). For the ADHD Index subscale of the CAARS, the groups showed a significant different levels of ADHD symptoms

($t(54) = -14.766$, $p < 0.0001$). For the WFIRS and the EFI scale, the group with higher ADHD scores demonstrated more functional impairments ($t(54) = -7.013$, $p < 0.0001$) and reported lower executive functions, ($t(54) = 5.851$, $p < 0.0001$) than group with lower ADHD scores, see Table 1.

3.2. Error characteristics

Both groups did not differ in the total amount of errors ($p = 0.456$), the group with higher and lower ADHD symptoms made respectively 110 and 101 errors. In the group with lower ADHD scores the RT of errors was slower ($M = 772$ ms, $SD = 94$ ms) than correct responses ($M = 726$ ms, $SD = 71$ ms) ($t(25) = -3.631$, $p = 0.001$). In the group with higher ADHD scores the RT of errors was similar ($M = 723$ ms, $SD = 120$ ms) to correct responses ($M = 717$ ms, $SD = 88$ ms) ($p = 0.622$).

3.3. Analyses on post-error slowing

In the RVF-RVF trial sequences responses after errors were slower than after correct responses, while in the LVF-LVF trial sequences responses after errors were similar to responses after correct responses. The repeated measure analysis of variance indicated a significant interaction between *correctness* and *visual field* ($F(1,54) = 10.807$, $p = 0.002$, $\eta^2 = 0.17$). In the RVF-RVF trial sequences, the mean RT after errors and correct responses were respectively 738 ms ($SD = 88$ ms) and 709 ms ($SD = 80$ ms). In the LVF-LVF trial sequences, the mean RT after errors and correct responses were respectively 738 ms ($SD = 87$ ms) and 740 ms ($SD = 92$ ms). Differences in post-error slowing between the RVF-RVF and LVF-LVF trial sequences were more pronounced in the slower stimulus presentation rate than in the fast rate, as suggested by a significant interaction between *correctness*, *visual field*, and *stimulus presentation rate* ($F(1,54) = 10.265$, $p = 0.002$, $\eta^2 = 0.16$). No other effects were significant ($p \geq 0.21$).

Fig. 1 shows that both groups differed in post-error slowing (the differences between post-correct and post-error trials) in the RVF-RVF trial sequences in the slower presentation rate only, while in the LVF-LVF trial sequences groups were similar in both presentation rates. This was statistically confirmed by a significant interaction between *group*, *correctness*, *visual field*, and *stimulus presentation rate* ($F(1,54) = 4.134$, $p = 0.047$, $\eta^2 = 0.07$). No other effects were significant ($p \geq 0.52$).

Using the more precise measurement of post-error slowing proposed by Dutilh, van Ravenzwaaij, et al. (2012), analysis showed that in the slower condition the group with lower ADHD scores tended to show increased post-error slowing than the group with higher ADHD scores, while in the fast condition both groups were similar. This was suggested by a marginally significant interaction between *group* and *stimulus presentation rate* ($F(1,54) = 3.621$, $p = 0.06$, $\eta^2 = 0.06$). In the fast condition the mean size of post-error slowing in subjects with higher and lower ADHD scores was respectively 23 ms ($SD = 37$ ms) and 20 ms ($SD = 39$ ms). In the slower condition the mean size of post-error slowing in subjects with higher and lower ADHD scores was respectively 9 ms ($SD = 54$ ms) and 41 ms ($SD = 48$ ms). Post-hoc analyses indicated that in the slower condition subjects with higher ADHD scores had a significantly decreased post-error slowing compared to those with lower ADHD scores ($t(54) = 2.327$, $p = 0.024$), whereas, in the fast condition no significant group difference was found ($t(54) = -0.300$, $p = 0.766$).

3.4. Analyses on post-error accuracy

During the slower stimulus presentation rate the RVF-RVF performance was more accurate after errors ($M = 87.06\%$, $SD = 22.99\%$)

Fig. 1. Mean reaction times of correct trials following correct and incorrect responses in each visual field and presentation rate. Note; Post-correct = RT for correct responses after correct trials; Post-error = RT for correct responses after errors; Fast Event Rate = the fast stimulus presentation rate condition; Slow Event Rate = the slower stimulus presentation rate condition; High ADHD Group = participants with scores fall in the third tertile of ADHD index scores; Low ADHD Group = participants with scores fall in the first tertile of ADHD index scores; LVF = left visual field; RVF = right visual field; Error bars indicate SE values.

compared to performance after correct responses ($M = 81.04\%$, $SD = 10.67\%$), while the LVF-LVF performance was similar between trials after errors ($M = 82.06\%$, $SD = 18.01\%$) and correct responses ($M = 82.19\%$, $SD = 10.18\%$). In contrast, during the fast stimulus presentation rate, response accuracy after errors was similar to that after correct responses in each visual field. For the RVF-RVF trial sequences the mean post-error and post-correct response accuracy were respectively 85.60% ($SD = 14.12\%$) and 88.48% ($SD = 6.57\%$). For the LVF-LVF trial sequences the mean post-error and post-correct response accuracy were respectively 82.96% ($SD = 11.43\%$) and 82.74% ($SD = 7.44\%$). This outcome was supported by a significant interaction between *correctness*, *visual field*, and *stimulus presentation rate* ($F(1,54) = 11.889$, $p = 0.001$, $\eta^2 = 0.18$). No other effects were significant ($p \geq 0.211$). With respect to group differences, the interaction between *group*, *correctness*, *visual field*, and *stimulus presentation rate* was not significant, as well as other group interactions ($p \geq 0.41$). Testing group differences in the RVF-RVF and LVF-LVF trial sequences apart showed that, in the RVF-RVF trial sequences subjects with lower ADHD scores showed enhanced accuracy after errors ($M = 89.56\%$, $SD = 7.20\%$) compared to accuracy after correct responses ($M = 84.27\%$, $SD = 7.24\%$), while subjects with higher ADHD scores had similar accuracy after errors ($M = 84.38\%$, $SD = 15.52\%$) and correct responses ($M = 85.16\%$, $SD = 8.14\%$). This finding was indicated by a marginally significant interaction between *group* and *correctness* ($F(1,54) = 3.965$, $p = 0.052$, $\eta^2 = 0.07$). For the LVF-LVF trial sequences no group interactions were found ($p \geq 0.15$).

The *responding hand* had no significant interaction with any of the variables: *correctness*, *stimulus presentation rate*, *visual field*, and *group* ($p \geq 0.291$), indicating that our results were not confounded by the responding hand.

The aforementioned findings (derived from the analyses on both post-error slowing and accuracy) were not substantially changed when testing the differences between the 19 subjects who reported ADHD diagnosis and those with lower ADHD scores. Analyses after excluding the 19 subjects showed no group differences. This null finding may be caused by low statistical power or that clinical cases are mainly responsible for the group differences.

4. Discussion

The aim of the present study is to investigate the contribution of the left and right hemisphere and the regulation of motor activation state via effort allocation to post-error adjustments in subjects with lower and higher ADHD symptoms. Analysis on the RT of all errors and correct responses suggests that the groups used different strategies to carry out the task. The control group with lower ADHD symptoms performed according to the deadline model (Yellott, 1971). Here, subjects estimate their own deadline needed for stimulus processing, decision making and responding. Responses within the deadline have a high probability to be correct. When the deadline has passed, stimulus evaluation and decision-making stops and a guess is made. Such responses have a high probability to be errors and are by definition slower than responses made before the deadline. In contrast, reaction times of correct responses and errors were roughly equal in the group with high level of ADHD, which might indicate impulsive and careless responding. These responses have a probability of 50 percent to be correct. So, a certain amount of correct responses are in fact based on guesses. It must be underlined that the responses of the group with higher ADHD scores did not conform the accumulation model, which assumes that a response is given when a threshold certainty of correctness is passed. Responses given before the threshold have a high probability to be inaccurate. This means that incorrect responses are faster than correct ones representing a speed-accuracy trade-off (Pachella & Pew, 1968). The absence of a speed-accuracy trade-off is frequently found in the response profile of ADHD, as reviewed by van der Meere (2005).

All in all, there are reasons to assume that the finding that the two groups did not differ in the overall number of errors is confounded by the different response strategies used by the two groups: part of the correct responses could be seen as correct responses by chance. Consequently, groups were different in their error processing, which is the topic of the present study.

4.1. Hemispheric asymmetry in post-error adjustments and ADHD symptoms

It was found that in control subjects with lower ADHD scores, post-error adjustments (response slowing and improved accuracy) occurred when errors were committed towards target stimuli presented in the RVF. Errors towards target stimuli presented in the LVF did not affect performance. As expected from the literature, post-error adjustments were absent in the group with higher ADHD scores, supporting the majority of studies showing that ADHD symptomatology is associated with poor post-error adjustments (Balogh & Czobor, 2014). However, in a comparable sample to ours, Chang, Davies, and Gavin (2009) investigated error monitoring during flanker performance and reported normal post-error slowing in university students with ADHD. It has been shown that during flanker performance the brain responds bilaterally to

errors (Taylor et al., 2006). This outcome together with the present outcome suggests that deviant error processing in ADHD might be more specific to left hemisphere dysfunctions.

In addition, the present outcome is consistent with much research that indicates the left hemisphere to be more involved in error processing. A study by Hochman et al. (2009), using a lateralized lexical decision task, showed left hemisphere dominance for the ERN amplitude during error correction. Another study by Swick and Turken (2002) reported that a lesion to the left region of Anterior Cingulate Cortex (ACC) is associated with less corrective behaviours and reduced ERN. An fMRI study on error processing and lateralized brain activity using a go/no-go task found that the left region of ACC was activated only for errors; while the right ACC was activated during correct responses and errors (Lütcke & Frahm, 2008). Stephan et al. (2003) indicated that lateralized activity of the ACC, which mediates cognitive control processes including error processing, depends on the task type. That is to say, the left ACC is more active during a verbal task, while, the right ACC is more active during a visuospatial task. This may explain why, in our verbal task, the left hemisphere was more involved in error processing.

The present outcome is also in line with behavioural research indicating that post-error slowing is more pronounced in the left hemisphere than in the right hemisphere. However, with respect to post-error accuracy our outcomes are at odds with outcome of some lateralization studies showing a right hemisphere dominance for improving post-error accuracy (Iacoboni et al., 1997; Kaplan & Zaidel, 2001; Narr et al., 2003; Stein & Zaidel, 1987; Zaidel et al., 1990). Discrepancy in findings might be caused by different experimental settings. For instance, some studies used feedback (Kaplan & Zaidel, 2001; Stein & Zaidel, 1987) in which feedback was presented in both visual fields implying that the two hemispheres get explicit information about the performance (external error processing) and therefore preventing automatic detection of error making. In our study, error processing was the result of spontaneous error detection (internal error processing). External and internal error processing may have different hemispheric involvement. Of more importance is that negative feedback after errors loads on the emotional system, which in turn may enhance the right-hemisphere ability to compensate for errors (Kaplan & Zaidel, 2001; Luu, Collins, & Tucker, 2000).

The present study contributes to the issue whether post-error slowing and increased post-error accuracy reflect the same neural mechanism (Fiehler et al., 2005; Hajcak & Simons, 2008; Hajcak et al., 2003; King et al., 2010). In our study post-error slowing occurred together with improved post-error accuracy in the RVF. Therefore, it is suggested that both post-error adjustments reflect the same neural mechanism and postulated in the left hemisphere. Here, an adaptive mechanism is operational that induces more cautious responses after errors in order to improve task performance (error monitoring). In this vein, the outcome of the present study does neither support the orienting account (Dutilh, Vandekerckhove, et al., 2012; Notebaert et al., 2009) nor the idea that post-error slowing attributes to the persistence of malfunction process from a previous trial to a current trial (Gehring & Fencsik, 2001; Gehring et al., 1993).

4.2. State regulation and error monitoring in adults with higher ADHD symptoms

Exploring the independent effect of the presentation rate of stimuli, irrespective of brain laterality effects, on error processing indicated that the overall size of post-error slowing, as expected from a meta-analysis of Balogh and Czobor (2014), was most pronounced in the slower condition in the control group and diminished in the group with high ADHD scores. This finding supports

the rule of thumb: the slower is the presentation rate, the poorer is the cognitive information processing (in the present study: error processing) in subjects with high ADHD due to less effort allocation needed to adjust performance after an error.

The finding that subjects with higher ADHD scores showed no post error slowing in the condition combining the RVF stimuli with slow stimulus presentation rate supports our hypothesis that poor error processing in ADHD is shaped by the interplay of state regulation and the left hemisphere-functioning. Given the facts that the left hemisphere is specialized in regulating the motor activation state via dopaminergic neurons (Declerck et al., 2004; Tucker & Williamson, 1984) and that slower stimulus presentation rates induce low motor activation state (van der Meere, 2005; van der Meere et al., 2010), the finding might be interpreted in terms of weak left hemisphere functioning to compensate for the low motor activation state.

In sum, findings support the hypothesis that poor cognitive performance in ADHD symptoms is associated with state regulation. According to the state regulation theory (Sanders, 1983), elementary cognitive processes such as stimulus identification, evaluation and subsequent motor reactions are in need for a sufficient amount of energy to fulfil the task requirements. The so-called input stages of information processing receive energy from the energetic arousal pool. The motor output stages are linked with the energetic activation pool. The energy levels in these pools are controlled by a so-called evaluation mechanism. The evaluation mechanism monitors whether the elementary cognitive processes receive too much or too little energy to function optimally (for reviews see Sonuga-Barke et al., 2010; van der Meere et al., 2010). The evaluation mechanism is also responsible for error detection, monitoring and correction (Sergeant, 2000). The majority of state regulation studies in ADHD using behavioural observations, heart rate variability, event related potentials (reviewed by van der Meere et al., 2010) and fMRI (Kooistra et al., 2010; Metin et al., 2015) point into the direction that the under-activation is the key. However, the hypothesis is primarily based on characteristics of correct responses. By investigating the state regulation factor (effects of stimulus presentation rate) during error processing the outcome of the present study supports that the interaction between the evaluation mechanism and the motor activation is compromised in ADHD.

One might link error processing to high reaction time variability found in ADHD (Kofler et al., 2013). High reaction time variability appears to be specifically related to the slow stimulus presentation rates due to difficulty in allocating sufficient effort to moderate the variability in the activation level (Metin et al., 2016). This may cause a drop in response preparation and leads to diminished post-error response adjustments in ADHD. Unfortunately, in the present study we could not investigate group differences in reaction time variability for two main reasons. First, the number of trials following errors were not enough to calculate RT variability after errors. Second, most errors might possibly occurred at a specific duration of the task (i.e., at the beginning or the end of the task), which might vary between the participants. Given the fact that RT variability is a mean to quantify how a set of data values is fluctuated over time, it was difficult to have a precise estimation of RT variability related to errors.

4.3. Other methodological considerations

So far, most of the previous studies on error processing focused on children fulfilling the ADHD-DSM diagnosis. They show weak error monitoring defined in terms of absence of post-error slowing together with reduced error related brain potentials (see review Shields & Hawk, 2010). In adults the research outcome is less easy to interpret. Three out of four studies showed compromised error

processing as far as error related brain potentials are concerned. However, they failed to find group differences in post-error adjustments (Chang et al., 2009; Herrmann et al., 2010; O'Connell et al., 2009; Wiersema, van der Meere, & Roeyers, 2009). What these studies have in common is a relatively fast presentation rate of stimuli. The present study using fast and slower stimulus presentation rates found attenuated post-error slowing in adults with higher ADHD scores during the slower condition. Unfortunately, no EEG registrations were carried out. Consequently, future EEG studies are needed to explore whether poor error processing at the performance level during a slow stimulus presentation rate goes hand in hand with reduced error related brain potentials in adults with higher level of ADHD symptoms.

4.4. Limitation

Lexical performance is impaired in adults with ADHD (Hale et al., 2005), and indeed, several studies have provided clear evidence that subjects with ADHD have language impairments (Bellani, Moretti, Perlini, & Brambilla, 2011; Bruce, Thernlund, & Nettelbladt, 2006). Therefore, deficits in post-error adjustments may be due to lexical problems in ADHD rather than error processing or at least confound the present findings. Having said that, adults with higher and lower ADHD symptoms perform equally well in the fast presentation rate condition indicating the language impairments did not play a role in post-error adjustments.

Although participants refrained from using medication at least 24 h before their participation, the effect of medication on performance cannot be ruled out. In addition, there might have been hidden comorbidities (Wolf, 2001), especially in the 19 participants who reported a DSM diagnosis of ADHD, which may confound the present findings and limits its generalizability.

4.5. Conclusion

The present behavioural study found that adults with higher level of ADHD symptoms have attenuated post-error response adjustments. In adults with higher level of ADHD symptoms, the left hemisphere ability to compensate for errors by slowing down responses to improve performance on a subsequent trial seems to be affected, particularly when extra effort allocation is needed to optimize the motor activation state.

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