To err is (perfectly) human: behavioural and neural correlates of error processing and perfectionism

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Abstract

The attitude towards one's own imperfection strongly varies between individuals. Here, we investigated variations in error-related activity depending on two sub-traits of perfectionism, *Personal Standard Perfectionism* (PSP) and *Evaluative Concern Perfectionism* (ECP) in a large scale functional magnetic resonance imaging study (N = 75) using a digit-flanker task. Participants with *higher PSP* scores showed both more post-error slowing and more neural activity in the medial-frontal gyrus including anterior cingulate cortex after errors. Interestingly, *high-EC* perfectionists with *low PSP* showed no post-error slowing and the highest activity in the middle frontal gyrus, whereas *high-EC* perfectionists with *high PSP* showed the lowest activity in this brain area and more post-error slowing. Our findings are in line with the hypothesis that perfectionists with *high* concerns but *low* standards avoid performance monitoring to avoid the worry-inducing nature of detecting personal failure and the anticipation of poor evaluation by others. However, the stronger goal-oriented performance motivation of perfectionists with *high* concerns and *high* standards may have led to less avoidance of error processing and a more intense involvement with the imperfect behaviour, which is essential for improving future performance.

Key words: performance monitoring; behavioural adaptation; personal standard perfectionism; evaluative concern perfectionism; functional magnetic resonance imaging (fMRI)

Introduction

Perfectionism can be boon and bane at the same time. A perfect performance is usually desirable because it fulfils a behavioural goal and results in positive outcome evaluations. Despite knowledge that a perfect performance is not always attainable, imperfections can lead to an agent's discontent. In extreme cases this discontent is accompanied by severe, clinically relevant symptoms such as depression (e.g. Asseraf and Vaillancourt, 2015), eating disorders (e.g. Reilly *et al.*, 2016), obsessive compulsive disorders (e.g. Boisseau *et al.*, 2013), psychosomatic syndromes (e.g. Herpertz-Dahlmann *et al.*, 2011) and anxiety disorders (e.g. Klibert *et al.*, 2015). A large body of research on the 'dark side' of perfectionism exists; however, its 'bright side', such as constructive involvement with the quality of one's own
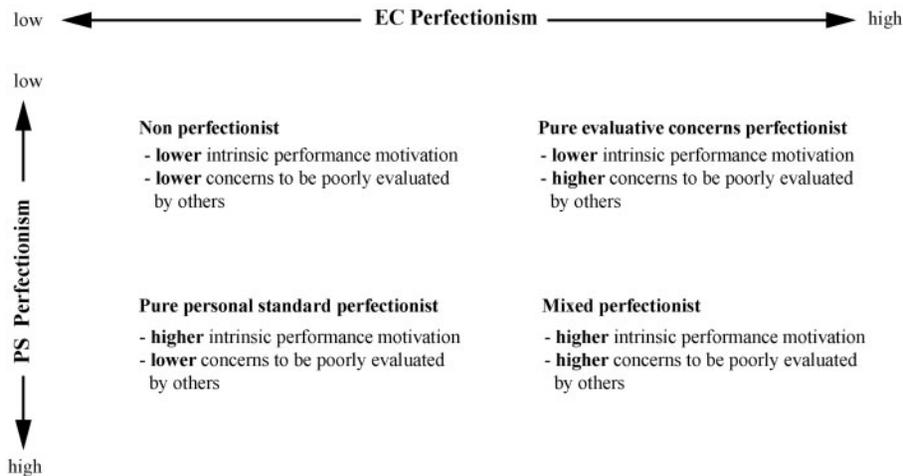
Fig. 1. Illustration of the two-dimensional perfectionism model of Gaudreau and Thompson (2010). This is a dimensional model, which additionally allows labelling four sub-groups based on the sub-trait combinations of personal standard (PS) perfectionism and evaluative concern (EC) perfectionism. Note that the two dimensions are positively correlated; orthogonality of the two dimensions is not postulated for this model.

performance and its improvement, is less well investigated (Stoeber and Otto, 2006).

Unquestionably, errors are crucial events for perfectionists, because errors provide information to optimize future behaviour, but can also be accompanied by unpleasant cognitions and feelings related to blame, shame and failure. Two studies reported perfectionism-related variations in error-processing and behavioural adaptation (Stahl *et al.*, 2015; Drizinsky *et al.*, 2016) indexed by two electrophysiological correlates, the error-related negativity (Ne/ERN) and error positivity (Pe) (Falkenstein *et al.*, 1991; Gehring *et al.*, 1993). These are well-established neural indicators of post-response processing related to (un-)aware error detection and post-error adaptation (e.g. Danielmeier and Ullsperger, 2011). Stahl *et al.* (2015) investigated perfectionism-related variations in performance monitoring based on the two-dimensional perfectionism model of Gaudreau and Thompson (2010). The first dimension, *evaluative concerns perfectionism* (ECP), characterizes the degree of negative cognitions and feelings related to erroneous performances, such as anticipating and worrying about poor evaluations by others. The second dimension, *personal standard perfectionism* (PSP), refers to setting criteria when evaluating one's own performance. People who score highly on this dimension (but not on ECP) set high criteria for their own performance and are highly motivated to fulfil these individual criteria to reach their goals. By combining the two dimensions, four sub-types of perfectionists can be characterized: non-perfectionist, pure-PS perfectionist, pure-EC perfectionist and mixed-perfectionists[1] (see Figure 1).

Electrophysiological findings from Stahl *et al.* (2015) indicated that, compared to the other three sub-types, pure-EC perfectionists process errors more superficially: they exhibited less error-processing activity as indicated by a reduced Ne/ERN amplitude and poorer behavioural adaptation after error commission. In contrast, for individuals characterized by both higher ECP scores

and higher PSP scores (i.e. mixed perfectionists), the high motivation of PSP seems to prevail over the high concerns. These participants showed the most profound error processing of all sub-types with both larger Ne/ERN amplitudes and better post-error adaptation. At first glance, these findings seem to challenge reports that participants with a stronger tendency to worry (related to anxiety, depression etc.) exhibited a higher Ne/ERN, as indicated by a meta-analysis (Moser *et al.*, 2013). Moser *et al.* (2013) attributed the larger Ne/ERN to more neural resources being recruited for re-allocation of attention from task-unspecific worry to task-specific response monitoring. However, Stahl *et al.* (2015) argued that only participants who have high intrinsic motivation in addition to a higher ECP score (i.e. mixed perfectionists) re-allocate their attention. In contrast, participants who are only very worried about evaluation but lack intrinsic performance motivation (i.e. pure-EC perfectionists) may fail to re-allocate their attention to response monitoring.

In summary, these and other electrophysiological findings (Pieters *et al.*, 2007; Tops *et al.*, 2013; Stahl *et al.*, 2015; Drizinsky *et al.*, 2016) pointed towards potentially crucial differences in error-related neural mechanisms in perfectionism subtypes. Here, we investigated perfectionism-related variations in response monitoring using functional magnetic resonance imaging (fMRI). To this end, we conducted a large scale fMRI study with eighty participants, using a speeded digit flanker paradigm with similar task requirements (Stahl, 2010), which provoked a sufficiently high number of error trials. We assessed participants' PSP and ECP scores to investigate dimensional variations in behavioural adaptation in relation to the Blood-Oxygenation-Level-Dependent (BOLD) signal.

Materials and methods

Participants

Considering a medium effect size ($\eta_p^2 = 0.1$), 80% power and 5% Type-I-error, according to an a *priori* power analysis (G*Power; Faul *et al.*, 2007), we aimed for a minimum sample size of 73. To account for possible technical problems, we recorded data from 80 psychology students (University of Göttingen, Germany). Five datasets were excluded from further analyses because of either strong motion artefacts (N = 4) or insufficient language skills to

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1 A categorisation based on continuous personality scores is arbitrary, especially for participants scoring close to the categorisation threshold. Note that the statistical analyses of the previous studies (e.g. Drizinsky *et al.*, 2016; Stahl *et al.*, 2015) as well as the present study are based on the continuous personality scores to account for the variations across the entire ranges of PSP and ECP. Solely for the sake of simplified description, we use the labels of the four sub-types.
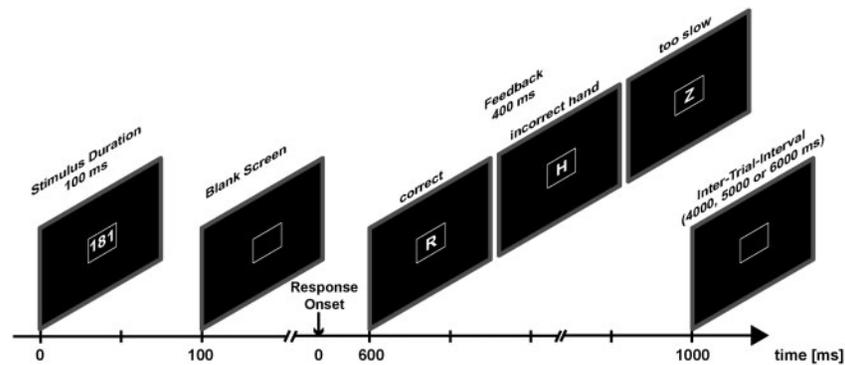
Fig. 2. Trial timing of the speeded digit-flanker task. The participant indicated whether the central digit on the screen was odd or even, while congruent or incongruent flankers were presented. The feedback (i.e. the initial letter of the German words for 'correct', 'hand' and 'time') was presented 600 ms after response onset. The inter-trial interval was jittered (i.e. 4000, 5000 or 6000 ms, equally distributed, randomly drawn).

respond to the questionnaire reliably (N = 1). The final sample consisted of 75 participants (61 female, mean age ± standard deviation: 22.2 ± 3.3 years, range 18 to 37 years; all right-handed). All participants reported normal or corrected-to-normal vision. None of the participants reported a neurological or psychiatric disorder. Participants received course credits for their participation and gave informed written consent prior to the investigation, and ethics committee approval was obtained.

Psychometric assessment

The German version of Frost's multidimensional perfectionism scale (FMPS; Altstötter-Gleich and Bergemann, 2006) was used to assess PSP using the *personal standard scale* (seven items, e.g. 'I am very good at focusing my efforts on attaining a goal') and ECP by the *concern over mistakes scale* (nine items, e.g. 'The fewer mistakes I make, the more people will like me.'). The item scales ranged from 0 (never) to 5 (always), and individual scores were computed by averaging the item scores. A significant positive relationship between PSP and ECP was found for the present sample ($r = 0.603$, $P < 0.01$), which is in line with previous studies (e.g. Frost *et al.*, 1990). No significant correlations between the perfectionism scores, age, and sex were obtained ($-0.167 \leq r \geq 0.113$, all $ps > 0.1$).

Procedure and experimental task

Participants completed a modified digit-flanker task (Stahl, 2010; see Figure 2 for the trial timing). The stimuli (three white digits on a black background in the centre of the display, e.g. 242 or 343) were presented using MR-compatible liquid crystal display goggles with a resolution of 800 x 600 pixels (Resonance Technology, Northridge, CA, USA). The participants responded to the parity of the central digit with a button press using the left or right hand (response box: MR-compatible fibre optic 4-button response pad; Current Designs, Philadelphia, PA, USA) as fast and accurately as possible. Half of the trials contained incongruent flanker to provoke performance errors. The stimulus-response hand assignment was balanced across participants.

A practise block contained 40 trials. The experiment itself consisted of three functional runs (126 trials per run with randomized stimulus order; duration of each functional run 9 min). In order to obtain a sufficient number of error trials, we applied an individual response time (RT) criterion (mean RT of the practice block minus 10%[2]; Stahl, 2010); too slow responses were excluded from further analyses (except from the post-

response analyses, see below). An error was defined as the use of the incorrect hand. Trial-by-trial performance feedback was given for correct, hand error, and time error (too slow).

Data acquisition

A 3 Tesla MRI scanner (Siemens Magnetom TIM Trio, Siemens Healthcare, Erlangen, Germany) with an 8-channel phased-array head coil was used for acquisition of the MRI scans. For the anatomical reference scans, a three-dimensional (3D) T1-weighted dataset was collected (turbo fast low angle shot; echo time (TE): 3.26 ms; repetition time (TR): 2250 ms; inversion time: 900 ms, flip angle 9°; isotropic resolution of 1x1x1 mm^3). For the functional images, a T2*-weighted gradient-echo echo-planar imaging (EPI) sequence was used (TE: 30 ms, TR: 2000 ms, flip angle 70°, 33 slices of 3-mm thickness at an in-plane resolution of 3x3 mm^2). One functional run contained 270 whole brain volumes.

Behavioural data analyses

Response time (RT; time interval between stimulus onset and response onset) and error rate (number of hand errors divided by total number of trials) were assessed. In order to compare post-error behaviour and post-correct response behaviour, we defined post-response RT difference (post-response RT_D) for error trials and for correct trials separately, based on the method suggested by Dutilh *et al.* (2012). For this, we subtracted the mean RT in trials *preceding* an error (or preceding a correct response) from the mean RT in trials *following* an error (or following a correct response). This estimate is more robust than the traditional post-error slowing estimates because it accounts for confounding effects of variations in RT across the duration of an experimental session, affecting the two response types differentially (Dutilh *et al.*, 2012). Post-response accuracy was calculated as the percentage of correct responses in trials following an error (e.g. 80% implies that 80% of the responses after all error trials were correct responses), or following a correct response, respectively.

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2   Neither PSP ($r = 0.12$, $p > .1$) nor ECP ($r = -0.01$, $p > 0.1$) showed a significant correlation with the individual RT criterion.

FMRI pre-processing and definition of regions-of-interest

All data were pre-processed using standard procedures as implemented in SPM8 (http://www.fil.ion.ucl.ac.uk/spm/). EPIs were realigned to the first image of the first run in order to correct for head motion. The EPIs were then slice-time corrected. Normalization to Montreal Neurological Institute (MNI) space was performed by co-registering all individual functional datasets to the structural T1 dataset of each participant first, and then normalising to the SPM template. Finally, normalized datasets were spatially smoothed with a Gaussian kernel of 8 mm full width at half maximum to account for anatomical variability and to satisfy the assumption of Gaussian random field theory. Data were high-pass filtered with a cut-off period of 128 s.

Next, a general linear model (GLM) was constructed to model three different conditions: (a) correct trials, (b) (hand) error trials and (c) too slow responses/other responses (which were of no interest here). For this, the onsets of the stimuli were used as the event onsets and convolved with the canonical haemodynamic response function (HRF) to obtain the regressors. Because responses were given directly following stimulus presentation, the regressor captured both stimulus presentation and responses as these fell in the time period < 1 TR. The six head movement parameters were entered as covariates-of-no-interest. Group-level statistical analyses were conducted (random effects analyses as implemented in SPM8) to test which brain regions were more strongly activated for errors compared to correct responses (contrast: errors > correct) as well as the reverse (contrast: correct > errors), using two one-sided t-tests, and applying a conservative threshold of $P < 0.05$ with family-wise error (FWE) correction for multiple comparisons at a voxel level. Additionally, we only considered clusters with > 30 voxels as meaningful. The resulting clusters were considered generally relevant to error processing and extracted as regions-of-interest (ROIs) for subsequent analyses.

Statistical analyses

Analyses of behavioural data. First, analyses of variance (ANOVA) with the within-subject factor response type (correct, error) were applied to the following dependent behavioural measures: RT, post-response RT_D, and post-response accuracy.

Analyses of fMRI data. The individual BOLD responses (beta estimates) for the baseline contrasts for correct-response regressors and error-response regressors were extracted from all ROIs (which were originally defined by the two contrasts error > correct, and correct > error; see above) using the MarsBaR toolbox (Brett *et al.*, 2002). Analogous to the behavioural data analyses, these data were then entered into GLMs with response type (correct, errors) as within-subject factor as well as the continuous predictors (ECP, PSP and PSP x ECP). We were not interested in the main effect of response type as it was used to select the ROIs in the whole brain analysis and therefore interpreting it would be circular (Kriegeskorte *et al.*, 2009). Hence, we focussed on the effects of the perfectionism-related variables as well as on potential response type x perfectionism interactions. If required, regression-based post-hoc tests were performed and simple slopes were calculated. Due to a large number of moderated regression analyses of for the selected ROIs, we accounted for the false discovery rate by using the Benjamini–Hochberg (1995) procedure. All correlation coefficients were Pearson's correlations (reported in Supplementary data SI). Effect sizes are reported as partial η_p^2.

Results

Error-correct contrast

Behavioural data. The mean ($\pm$ standard error of mean) error rate was $15.0 \pm 0.64\%$, (ranging from 5.99% to 31.51%), the percentage of slow responses was $23.68 \pm 1.12\%$ (ranging from 9.64 to 56.51%). Slow response trials were discarded from further analyses. An ANOVA on RT showed that responses were significantly faster in error trials (446 ± 4.91 ms) compared to correct responses (457 ± 4.46 ms), $F(1,74) = 87.81$, $P < 0.001$, $\eta_p^2 = 0.54$. Two further ANOVAs performed on post-response behaviour showed that participants were slower *after* error trials (post-response RT_D: 22.29 ± 2.44 ms; positive values indicate slowing in trial $n + 1$) than *after* correct responses ($–6.46 \pm 0.81$ ms), $F(1,74) = 95.75$, $P < 0.001$, $\eta_p^2 = 0.56$. Additionally, they made more correct responses after errors (post-response accuracy: $86.11 \pm 0.08\%$), than after correct responses ($84.07 \pm 0.07\%$), $F(1,74) = 7.89$, $P = 0.006$, $\eta_p^2 = 0.10$.

Whole brain fMRI analysis (ROI definition). Contrasting errors and correct responses in a whole brain analysis identified *three* regions in which the BOLD responses were significantly stronger for correct responses compared to errors (Set I) and *seven* regions in which the BOLD responses were stronger for error trials compared to correct responses (Set II, see Figure 3 and Table 1).

Set I consisted of a cluster in bilateral orbitofrontal cortex [cluster reference no. 1; see Table 1], as well as clusters in the left [2] and right putamen [3]. Set II included clusters in the left and right superior/middle frontal gyrus [5, 6], as well as a large cluster in the left and right medial-frontal cortex [4], expanding to the left and right anterior cingulate cortex (ACC). Significant clusters were also found in the left [7] and right insular cortex [8], the left middle frontal gyrus (MFG) [9] and the left supramarginal gyrus [10].

Perfectionism-related results

Perfectionism-related effects on behaviour. Analogous to previous studies (e.g. Stahl *et al.*, 2015), we performed moderated regression analyses, i.e. GLM analyses using the centralized scores of PSP, ECP and PSP x ECP as continuous predictors as well as response type (correct, error) as a within-subject factor (see Table 2). No significant perfectionism-related effect on the error rate was found (all Fs < 1.4, all Ps > 0.10, all $\eta_p^2 < 0.01$; response type not applicable). The GLM for RT did not yield a significant effect of any of the continuous predictors (all Fs < 1.66, all Ps > 0.10, all η_p^2 s < 0.03). Merely the ECP x Response Type interaction ($\beta_{correct} = 0.02$; $\beta_{error} = 0.07$) was close to reaching significance, $F(1,71) = 3.77$, $P = 0.056$, $\eta_p^2 = 0.05$.

A further GLM revealed a marginal effect of PSP on post-response RT_D, $F(1,74) = 3.34$, $P = 0.072$, $\eta_p^2 = 0.045$, but no effect of ECP, $F(1,74) < 1.3$, $P = 0.27$, $\eta_p^2 < 0.02$, and a significant PSP x Response Type interaction, $F(1,71) = 4.32$, $P = 0.041$, $\eta_p^2 = 0.06$. Post-hoc regression analysis revealed a positive relationship between PSP and post-response RT_D in error trials ($\beta = 0.22$, $P = 0.042$), and a negative relationship in correct trials ($\beta = –0.15$, $P = 0.19$). We also identified a significant PSP x ECP interaction, $F(1,71) = 13.16$, $P < 0.001$, $\eta_p^2 = 0.16$, ($\beta = 0.39$, $P < 0.001$; see also Supplementary data SIII) and a significant Response Type x PSP x ECP interaction, $F(1,71) = 7.86$, $P = 0.006$, $\eta_p^2 = 0.10$. This moderating effect of ECP on the relationship between PSP and post-response RT_D was investigated by using post-hoc tests based on simple-slope analyses. Figure 4 shows the three regression slopes, which were estimated for one standard deviation below
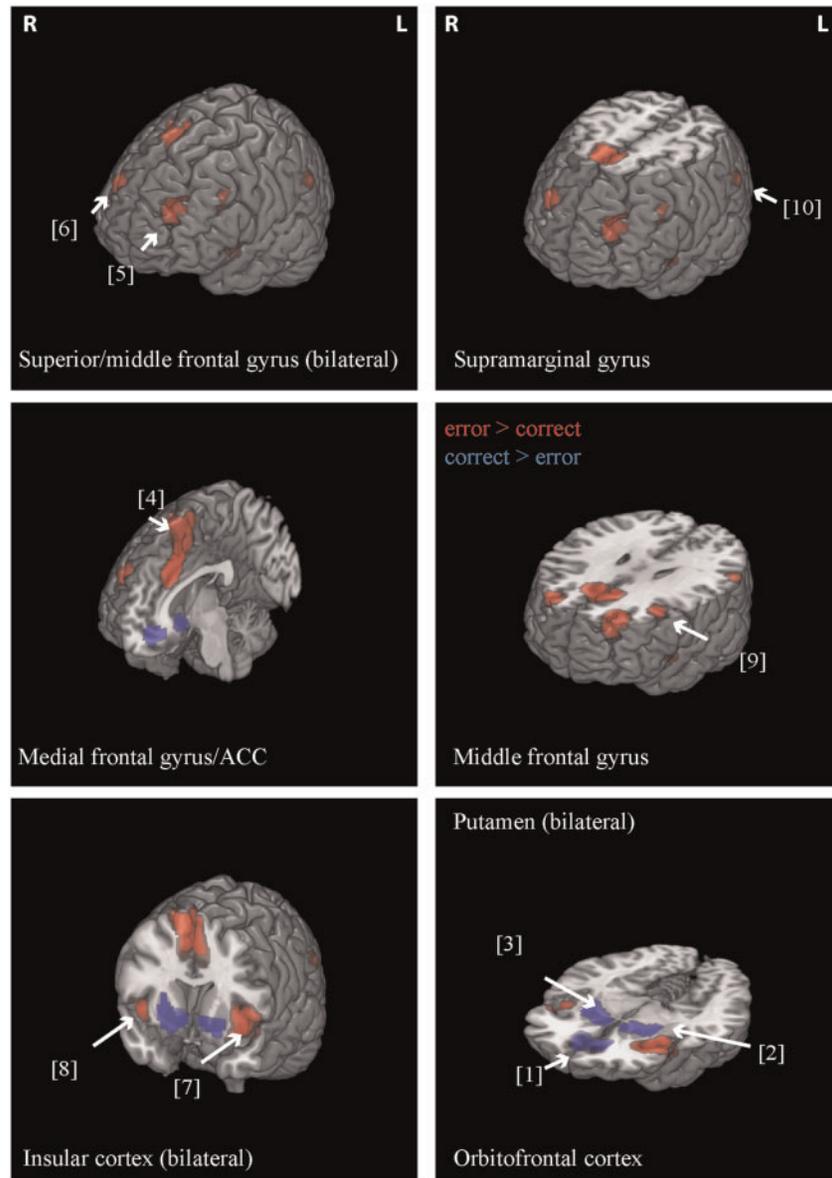
Fig. 3. Brain regions [cluster reference number, cf. Table 1] that showed significantly stronger BOLD responses for errors compared to correct responses (red regions) and for correct responses compared to errors (blue regions); FWE corrected alpha-level of $P < 0.05$; cluster-threshold: 30 voxels.

the mean ECP score (low ECP), matching the mean ECP scores (medium ECP), and one standard deviation above the mean ECP score (high ECP), separately for error trials (Figure 4A and B) and correct trials (Figure 4C and 3D). For error trials, the regression slopes for high EC perfectionists (simple $slope_{high} = 13.37$, $t(71) = 3.92$, $P < 0.001$) and for medium EC perfectionists (simple $slope_{mean} = 4.69$, $t(71) = 2.27$, $P = 0.042$) significantly differ from zero, indicating a positive relationship between PSP and post-error slowing for medium- and high EC perfectionists (Figure 4A, dashed and solid lines). For low-EC perfectionists (Figure 4A, dotted line), the relationship between PSP and post-response RT_D did not reach significance (simple $slope_{low} = -3.99$, $t(71) = 1.13$ $P = 0.26$). We did not observe any significant relationship for correct trials (all $Ps > 0.18$; no significant slope for any ECP score, Figure 4C and D). There was no significant relationship between PSP, ECP and post-response accuracy (all $Fs < 1.8$, all $Ps > 0.19$, all $\eta_p^2 s < 0.03$).

Perfectionism-related effects on BOLD responses. Analogously to the behavioural data, the individual mean BOLD responses resulting from the baseline contrasts ($BOLD_{cor}$, $BOLD_{err}$) from both sets of ROIs were subjected to separate moderated regression analyses. For the sake of brevity, we report only findings that show significant relationships with at least one of the perfectionism traits. All F values and significance levels are summarized in Table 2. For cluster set I ROIs, a main effect of PSP was observed for the left putamen [2], $F(1,71) = 5.73$, $P < 0.019$, $\eta_p^2 = 0.08$. The post-hoc regression analysis showed a main effect of PSP, that is a positive relationship between the mean $BOLD_{(err,cor)}$ and PSP ($\beta_{(err,cor)} = 0.27$, $P < 0.019$), indicating that higher BOLD activity with higher PSP scores occurred in both response types. No further significant effects were observed (all $Fs < 1.0$, all $Ps > 0.40$, all $\eta_p^2 s < 0.01$). The GLM for the BOLD responses of the right putamen [3] also showed a significant main effect of PSP, $F(1,71) = 9.01$, $P = 0.004$, $\eta_p^2 = 0.11$, with a

Table 1. Whole brain fMRI analyses for contrasting correct and error responses

Structure [Cluster reference number]	BA	L/R	MNI space			Cluster size 3 x 3 x 3 mm	t value (peak)
			X	y	Z		
Cluster set I: Contrast (correct > error)							
Orbitofrontal cortex [1]	11	L/R	−6	38	−11	184	6.75
Putamen [2]		L	−15	5	−14	169	8.92
Putamen [3]		R	15	8	−14	215	8.68
Cluster set II: Contrast (error > correct)							
Medial-frontal cortex including anterior cingulate cortex [4]	6/ 24	L/R L/R	9	11	64	760	9.21
Superior/middle frontal gyrus [5]	8/9	L	−24	44	28	179	9.21
Superior/middle frontal gyrus [6]	8/9	R	24	50	34	94	7.10
Insular cortex [7]	13	L	−39	17	−11	442	8.25
Insular cortex [8]	13	R	45	14	−5	110	5.91
Middle frontal gyrus [9]	9	L	−48	23	34	63	5.30
Supramarginal gyrus [10]	40	L	−60	−46	34	37	5.58

Notes Sources. Brodmann area (BA). L = left; R = Right; MNI = Montreal Neurological Institute coordinates; FWE corrected alpha-level of $P < 0.05$; 30 voxel cluster-threshold.

Table 2. F values from the general linear model analyses including response type (Resp: correct, errors) as a within-subject factor and personal standard (PCP) scores and evaluative concern perfectionism (ECP) scores as continuous predictors, separately performed for all behavioural data and BOLD responses extracted from significant regions of interests of the whole brain error-correct contrasts

	Resp	PSP	ECP	PSP x Resp	ECP x Resp	PSP x ECP	ResP x PSP x ECP
Behavioural data							
Error rate [%]	n.a.	1.32	0.01	n.a.	n.a.	0.66	n.a.
Response Time [ms]	89.02***	1.66	0.16	0.24	3.77+	0.49	0.21
Post-response RT_D [ms]	108.41***	3.34+	1.24	4.32*	0.80	13.16**	7.86**
Post-response Accuracy [%]	7.89**	1.49	0.02	1.75	0.00	0.43	1.15
Cluster set I:							
ROI-defining Contrast (correct > error)							
Orbito frontal cortex (L/R) [1][2]	−[1]	0.84	1.07	2.76	0.51	0.01	0.13
Putamen (L) [2]	−[1]	5.73*[a]	0.66	0.47	0.11	0.18	0.19
Putamen (R) [3]	−[1]	9.01** [a]	0.06	3.20+	0.21	0.08	0.73
Cluster set II:							
ROI-defining Contrast (error > correct)							
Medial-frontal cortex (L/R)/Anterior cingulate cortex (L/R) [4]	−[1]	5.00*[a]	0.60	4.57*[a]	0.83	0.28	0.89
Superior/middle frontal gyrus (L) [5]	−[1]	0.19	0.80	0.83	0.01	0.64	1.06
Superior/middle frontal gyrus (R) [6]	−[1]	1.58	0.98	3.94+	0.37	0.17	0.08
Insular cortex (L) [7]	−[1]	2.09	0.13	0.58	0.18	0.00	0.03
Insular cortex (R) [8]	−[1]	0.91	0.00	0.01	0.54	0.18	0.17
Middle frontal gyrus (L) [9]	−[1]	0.12	0.05	1.42	2.33	4.11*[b]	0.19
Supramarginal gyrus (L) [10]	−[1]	0.07	0.48	2.99+	1.28	0.02	0.23

Notes Sources. [1]Not reported since the regions of interests (ROI) resulted from significant error-correct contrasts; [2][Cluster reference number];
[a]Significant ($P < 0.05$) after controlling the BOLD response results for false discovery rate according to Benjamini–Hochberg (1995). L = left; R = right; RT_D = response time difference.
[b]Not significant after correction for multiple correction.
+$P < 0.08$; *$P < 0.05$, **$P < 0.01$, ***$P < 0.001$.

positive relationship between the mean $BOLD_{(err,cor)}$ response and PSP ($\beta_{(err,cor)} = 0.34$, $P < 0.004$). No further significant effects were found (all Fs < 1.0, all Ps > 0.10, all, $\eta_p^2 s < 0.01$) except for the PSP x Response Type interaction which approached significance, $F(1,71) = 3.20$, $P = 0.078$, $\eta_p^2 = 0.04$. It indicates that the PSP effect mainly resulted from $BOLD_{err}$ responses ($\beta_{err} = 0.33$, $P < 0.004$) but not from $BOLD_{cor}$ responses ($\beta_{cor} = 0.21$, $P = 0.064$).

For set II ROIs, the mean BOLD response of the medial-frontal cortex/ACC [4] was related to PSP, $F(1,71) = 5.00$, $P = 0.028$, $\eta_p^2 = 0.07$, and showed a PSP x Response Type interaction, $F(1,71) = 4.57$, $P = 0.036$, $\eta_p^2 = 0.06$. The first post-hoc regression analysis for the PSP main effect revealed a positive relationship between PSP and the mean $BOLD_{(err,cor)}$ response ($\beta_{(err,cor)} = 0.25$, $P < 0.028$), whereas the separate analyses for the response types showed clearly that the positive relationship mainly resulted from error trials ($\beta_{err} = 0.28$, $P = 0.016$) but not from correct trials ($\beta_{cor} = 0.1$, $P = 0.29$). No further significant effects were observed (all Fs < 1.0, all Ps > 0.34, all $\eta_p^2 s < 0.02$). Finally, a significant PSP
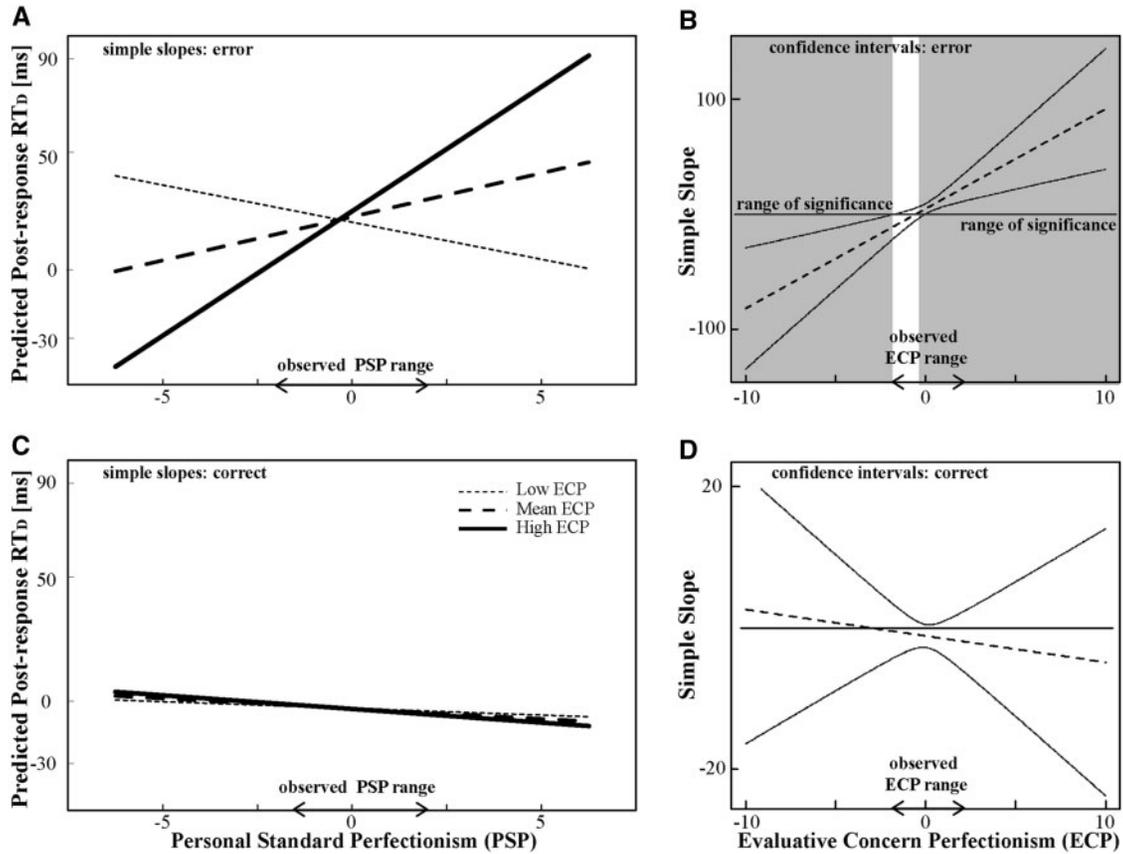
Fig. 4. Illustration of the simple-slope analyses for post-response response time difference (RT_D, i.e. post-response minus pre-response RT) for the PCP-by-ECP-by-Response-Type interaction (A, C). The depicted regression slopes were estimated for mean, and ±1 standard deviation of ECP scores (low/high): (A) post-error RT_D and (C) post-correct response RT_D. The right panels (B, D) show all theoretically possible simple slopes (dashed lines) for ECP. The grey areas (A) indicate the ranges of significance which are defined by the confidence intervals (solid lines) not including zero. The observed ranges of the *centralized* scores of ECP and PSP in our sample are indicated by arrow heads.
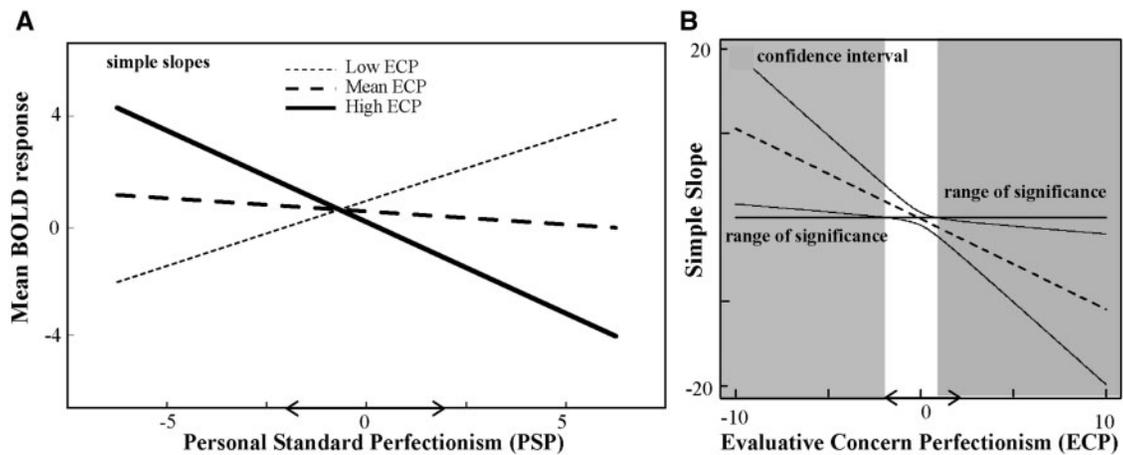
Fig. 5. Illustration of the simple-slope analyses for the predicted mean BOLD response (left middle frontal gyrus) [9] resulting from the moderated regression analysis for the PSP-by-ECP interaction (A). The depicted regression slopes were estimated for mean and ± 1 standard deviation of ECP scores (low/high). The right panel (B) shows simple slopes (dashed line) as a function of ECP. The grey areas indicate the range of significance which is defined by confidence range (solid lines) not including zero. The observed ranges of the *centralized* scores of ECP and PSP in our sample are indicated by arrow heads.

x ECP interaction was observed for the left MFG [9], $F(1,71) = 4.11$, $P < 0.046$, $\eta_p^2 = 0.06$. Note that the 5% significance level was not reached after correcting for multiple comparisons (see Table 2). For completeness sake, we nevertheless performed a simple slope analysis (Figure 5A, solid line), which

showed a negative relationship between PSP scores and the BOLD responses in this region for high ECP participants (simple slope$_{high} = -0.626$, $t(71) = -2.14$, $P = 0.035$). This result, however, should be interpreted with care. The observed interaction was independent of response type, which means that the

relationship was observed in error trials as well as in correct trials. The range of significance of the simple slopes (Figure 5B, right grey area) demonstrated significant negative slopes for all ECP scores above 0.7. For low- and medium-EC perfectionists, the slopes of the relationship between PSP and the BOLD response (Figure 5A, dotted line, dashed line) did not reach significance (e.g. simple slope$_{low}$ = 0.446, P = 0.14; simple slope$_{mean}$ = 0.09, P = 0.64). For lower ECP scores, the range of significance (i.e. below -1.97) was mainly beyond the observed sample's ECP score (Figure 5B); thus, this range should not be interpreted.

Discussion

In a large-scale fMRI study, we investigated perfectionism-related variations in both behavioural and neural correlates of error processing in a speeded response task. First, our fMRI results replicated the well-known findings of stronger neural activity for errors compared to correct responses in regions of the medial frontal cortex (including ACC), the insular cortex, the superior/middle frontal gyrus and the supramarginal gyrus, in addition to stronger BOLD responses for correct trials compared to errors in the putamen and the orbitofrontal cortex. Our results mirror previous findings showing that these areas are part of an error-processing network (e.g. Lütcke and Frahm, 2008; Luijten *et al.*, 2014; Steele *et al.*, 2014; Iannaccone *et al.*, 2015). Similar to other studies, only the left MFG showed an error-specific difference (e.g. Magno *et al.*, 2009). The relationships between behavioural parameters and neural activity were in line with previous research (for details, see Supplementary data SI and SII).

Perfectionism and performance processing

Behavioural findings. Similar to previous studies (Stahl *et al.*, 2015; Drizinsky *et al.*, 2016), we found no perfectionism-related variations in error rates or general response speed. However, high-PS perfectionists responded more slowly than the low-PS perfectionists *after error trials* but not *after correct trials*. Interestingly, ECP had a moderating effect in a way that only for high- and medium-EC perfectionists this positive relationship between post-error slowing and PSP was found, but this did not hold for low-EC perfectionists. As with previous research, no evidence for behavioural adaptation of pure-EC perfectionists, (higher ECP, lower PSP; cf. Figure 1; Footnote 1) was found (Stahl *et al.*, 2015). These findings may reflect an incapability, or a lack of motivation, to shift attention to performance monitoring due to the worry-inducing state of error detection for EC perfectionists. In turn, diminished performance monitoring limits the knowledge of error-related information, and allows the acting person to avoid anticipating the threat of poor evaluation by others at the price of missing out on information that may be relevant to improving one's performance. In contrast, high-EC perfectionists with higher PSP scores (mixed perfectionists) showed clear signs of post-error adaptation. This is in line with the hypothesis that these types of EC perfectionists are able to re-allocate their attention to performance monitoring (Stahl *et al.*, 2015), and that they use accumulated error-specific evidence (e.g. Bode and Stahl, 2014), as they have a high intrinsic motivation of performance improvement in addition to their concerns. Interestingly, in a recent study that induced extrinsic motivation for error detection using a trial-by-trial response-evaluation task (Drizinsky *et al.*, 2016), evidence of the accumulation of error-related information was also provided for

pure-EC perfectionists (low PSP). Under such externally induced motivation, the authors reported the highest Pe amplitude—an indicator of aware error processing—and better post-error adaptation for this group (pure-ECP), indicating that extrinsic motivation can modify the EC-perfectionists' error processing strategies just as intrinsic performance motivation can. Hence, pure-EC perfectionists are generally capable of re-allocating attention to performance monitoring; our behavioural results (see also Stahl *et al.*, 2015) additionally suggest that the behavioural expression might depend on the exact motivational circumstances.

Neural findings. For PS perfectionists (independent from ECP), we found a stronger BOLD response in error trials in the medial-frontal gyrus including the ACC—a region that is known to be involved in error-detection and response-conflict monitoring (e.g. Ridderinkhof *et al.*, 2004; Iannaccone *et al.*, 2015). Together with the increased post-error slowing, our data supported the assumption that high-PS perfectionists processed errors more intensively and used this information to improve their behaviour after an error commission (see also Debener *et al.*, 2005).

In contrast to our electrophysiology findings (Stahl *et al.*, 2015), no moderating effect of ECP on the relationship between PSP and the ACC activity was observed. The difference in the temporal resolution of event-related potentials and fMRI might explain this discrepancy. The ACC activity evoked by response processing and by feedback processing could be separated due to the high temporal resolution of the electroencephalography in the previous study. However, the 600-ms interval between error response and feedback is not sufficient to identify separate BOLD responses (as this interval was shorter than 1 TR); thus, the observed ACC activity may reflect both response and feedback processing. We cannot rule out that pure EC perfectionists, which showed the smallest Ne/ERN (Stahl *et al.*, 2015), process external feedback more intensively than their own internal error information. If this were true, diverging response-related activity and feedback-related activity could attenuate the moderating effect of ECP on ACC activity. Additionally, the BOLD responses of the (bilateral) putamen were positively correlated with PSP. The putamen is involved in reward processing and goal orientation (Linke *et al.*, 2010), in behavioural adaptation after error commission (Hester *et al.*, 2009), and the setting of individual response thresholds (e.g. Forstmann *et al.*, 2010). Hence, this activity could be taken to reflect the PS perfectionist's strong goal orientation, the tendency to improve their own performance after error commission and the cognitions, which are necessary to balance speed and accuracy.

The ECP-by-PSP interaction for the BOLD responses in the MFG reflected that participants with higher ECP scores showed a negative relationship between BOLD responses and PSP (cf. Figure 5), but no such relationship was found for participants with low ECP scores. This region has been shown to be involved in the re-allocation of attention (Japee *et al.*, 2015), as well as in the regulation of approach and avoidance (Spielberg *et al.*, 2011). At first glance, one could surmise that high-EC perfectionists may have recruited more neural resources re-allocating attention to performance monitoring if they were also low PS perfectionists (pure-ECP). However, this is the opposite of what our behavioural findings implied, and indeed, at a behavioural level they did not show behavioural adaptation after error commission (see above). Alternatively, the observed neural effect might be better explained by pure-EC perfectionists allocating more neural resources to explicitly *avoid* error processing, because attending to information related to a possible negative outcome

would induce worry about the evaluation of their behaviour. Furthermore, the neural activity was higher in both, error and correct response trials, which indicates that these participants did not differentiate between correct responses and errors, but rather suggests that they avoided performance monitoring in general, for example, as the result of a detrimental coping strategy. This interpretation would also fit with the proposed role of the MFG in the regulation of approach and avoidance (Spielberg *et al.*, 2011). On the behavioural level, the absence of a post-error adaptation in pure-EC perfectionists further supported the hypothesis of Stahl *et al.* (2015) (Drizinsky *et al.*, 2016) that pure-EC perfectionists avoided error processing (for details, see above). The present results are in line with our first EEG study (Stahl *et al.*, 2015), where pure-EC perfectionists, who showed smaller Ne/ERN amplitudes (an electrophysiological indicator for error-related ACC activity), also did not improve performance after errors, whereas mixed perfectionists, who showed higher Ne/ERN amplitudes clearly improved performance after error commission. Accordingly, the relatively lower BOLD response for high-EC perfectionists with high PSP scores (mixed perfectionists) in this region could be taken to indicate that they did not attempt to avoid processing the performance-improving (error-related) information as their PSP drove them to achieve better performance. Following this interpretation, one would further predict a lack of modulation of activation levels in all low-EC participants, given that the avoidance of performance monitoring would not play a role in their behaviour. This is also what we observed—the PSP score in low-EC participants (i.e. non-perfectionists or pure-PS perfectionists) had no effect on the BOLD signal in MFG, and all of these participants showed moderate levels of activity. However, these results should be interpreted with care, as the simple slope analysis was significant, but the interaction did not reach the level of significance after a correction for multiple comparisons. Note that our neural results allow no direct insights into the exact cognitive mechanisms in these perfectionist groups. To further dissociate the role of different cognitive processes contributing to sub-types of perfectionism, future research could systematically investigate the motivation to re-allocate attention to performance monitoring while more directly assessing the tendency to approach or avoid this process. Both, ACC and MFG contributed to the processing of negative performance outcomes such as errors as well as the avoidance of processing such negative outcomes (Magno *et al.*, 2009). Interestingly, we found that ECP moderated only the relationship between PSP and the BOLD response in the MFG, whereas no moderating effect was observed for the BOLD response in the ACC. One reason might be a functional dissociation between regions. The MFG, for example, has been shown to be sensitive to internal errors (such as response errors), but not to external error feedback (Nadig *et al.*, 2010), whereas the ACC was sensitive to both internal errors and external error feedback (see, Ridderinkhof *et al.*, 2004). If the MFG is less involved in feedback processing compared to the ACC, a more intense feedback processing of EC perfectionists might have masked the moderating effects in the ACC (for details see above). However, this assumption requires further tests, for example, by contrasting trials with and without feedback presentation, which we cannot perform with the present study.

Out of the 10 ROIs selected based on the error *vs* correct comparison, only a subset of these error processing regions exhibited modulations related to trait perfectionism. Given that our study is the first to investigate perfectionism-related variations in error processing, we can only carefully speculate on the absence of perfectionism-related activity in specific regions.

The pattern of results we found could result from differential involvement of these regions in this specific task, or because specific roles played by these regions do not differ with perfectionistic sub-traits. However, further research is needed to arbitrate between these scenarios. Error responses in speeded response tasks, which are usually used to investigate error processing, are usually faster than the correct responses (Rabbitt, 1966). This was also observed for our task. As RT variability could affect the BOLD response (e.g. Bellgrove *et al.*, 2004), we cannot rule out that the variations in RT contributed to the significant differences between the two conditions. However, these different RT profiles constitute an inevitable confound of all fMRI studies investigating error processing. We did not find any correlational relationship between RT and perfectionism scores; thus, our analyses of the perfectionism-related variations in BOLD responses should not be affected systematically by these RT differences.

Conclusions and implications

Our study provided evidence that sub-traits of perfectionism (PSP and ECP) had differential impact on behavioural adaptation, reflected in differences in neural processing related to performance monitoring. For high-PS perfectionists, stronger error-related signals were found in the medial frontal gryus/ACC presumably related to the extraction of error-specific information, which could be used to improve post-error behaviour. For high-EC perfectionists, the neural activity in the MFG was distinctly modulated by the PSP scores—participants with high ECP but low PSP scores showed the highest activation and the worst post-error adaptation. We argue that this most likely reflects a tendency to avoid re-allocating attention to performance monitoring. For high-EC perfectionists with high PSP, the intrinsic performance motivation might have overridden this tendency, which led to better performance and reduced activation in the MFG. Importantly, our findings demonstrate that while closely related, ECP and PSP are not just two sides of the same coin. These insights may facilitate the development of targeted interventions to reduce the detrimental effects of the avoidance of error processing, and to foster positive cognitive changes, such as acceptance of and a constructive perspective on imperfect actions.

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Supplementary data

Supplementary data are available at *SCAN* online.

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