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RESEARCH ARTICLE

Interpersonal traits and the neural representations of cognitive control in the prefrontal cortex

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Abstract

Adaptive interpersonal functioning relies on the effectiveness of behavioral and neural systems involved in cognitive control. Whether different subcomponents of cognitive control and their neural representations are associated with distinctive interpersonal dispositions has yet to be determined. The present study investigated the relationships between prefrontal cortex (PFC) activation associated with two subcomponents of cognitive control and individual differences in interpersonally relevant traits and facets within the Five-Factor Model of personality. Undergraduate participants (n = 237) provided self-ratings of interpersonal traits and underwent functional near-infrared spectroscopy to measure activation in regions-of-interest linked to subcomponents of cognitive control: the right lateral PFC and its involvement in response selection and inhibition/suppression (RS) during a go/no-go task, and the left lateral PFC associated with goal selection, updating, representation, and maintenance (GS) on a tower planning task. Multilevel models revealed that during both RS and GS, Neuroticism and Extraversion were associated with lower and higher levels of activation, respectively. Higher Agreeableness was related to lower activation during RS but also with greater activation during GS. More narrowly defined interpersonal facets subsumed within the broader trait domains were differentially associated with RS- and GS-related neural responses. Taken together, these findings highlight potential avenues of future research to better understand the ways in which the neural processes that subserve cognitive control may underlie interpersonal dispositions.

Keywords Interpersonal · Personality traits · Cognitive control · Prefrontal cortex

Introduction

The ability to optimally regulate our behavior is advantageous for survival. In particular, behavioral regulation is vital for succeeding in one's interpersonal milieu. A growing body of research supports the idea that an individual's overall ability to regulate cognition, affect, and behavior is linked to better interpersonal skills and outcomes across various contexts (Tangney et al., 2004). Specifically, it appears that those who are better able to regulate their behavior enjoy favorable interpersonal consequences, such as healthier relationships (e.g., forming secure attachments, experiencing fewer issues relating to anger and relationship conflict) and stronger interpersonal skills (e.g., being better able to take others' perspectives and show empathy). Additionally, injury to brain regions that are thought to subserve behavioral regulation have been linked to reduced interpersonal competence and more interpersonal problems (Yeates et al., 2004). Furthermore, psychiatric and neurodevelopmental disorders

Highlights
- Activation patterns for response- and goal-selection differed across interpersonal traits.
- Variability was also seen at the level of facets that constituted trait domains.
- Some facets showed patterns of associations that were distinct from their traits.

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that are linked to poor regulation of thoughts, emotions, and behaviors have been linked to less adaptive interpersonal functioning, such as impairments in social cognition (Uekermann et al., 2010), and higher prevalence of interpersonal problems (Salzer et al., 2013). Such evidence supports a general relationship between an individual's effectiveness in regulating their behavior and their ability to succeed with regard to interpersonal functioning (i.e., better regulation is associated with more favorable interpersonal outcomes). To date, however, the precise nature by which nuances in our ability to regulate behavior might influence interpersonal functioning has yet to be fully elucidated.

Interpersonal functioning as conceptualized in the five factor model of personality

While interpersonal functioning can be assessed in a number of ways, personality science provides a useful framework for understanding and quantifying human behavior within the interpersonal context. Personality traits, commonly conceptualized as enduring patterns of behavioral dispositions, form a key conceptual anchor for our understanding of how we behave with others (Tellegen, 1991). Within this context, the Five-Factor Model (FFM) of personality has emerged as a widely accepted conceptual framework that has unified much of the contemporary research on how we engage with others, as well as our environments more generally (John et al., 2008). Importantly, trait domains and their constituting facets within the FFM are useful tools for conceptualizing interpersonal functioning across both momentary (e.g., isolated interpersonal interactions) and longitudinal processes (e.g., attachment; Costa & McCrae, 2011). Therefore, trait domains and their facets within the FFM can help to meaningfully delineate how important constructs such as behavioral regulation may influence interpersonal functioning.

Key distinctions should be noted with regard to how personality traits and facets may relate to interpersonal functioning in general. While certain trait domains are suggested to be intrinsically interpersonal, the contribution of other trait domains to interpersonal functioning may be context dependent. Specifically, trait Extraversion (E), Agreeableness (A), and Neuroticism (N) define dispositions that are inherently interpersonal in nature, and for the most part, capture the complete gamut of interpersonal functioning (Costa & McCrae, 2011; DeYoung et al., 2013). Furthermore, it has been suggested that N represents a general risk factor for interpersonal dysfunction, which in turn may be expressed as a function of E and A. On the other hand, Conscientiousness (C) and Openness to experience (O) also may be relevant to how we engage with others, albeit indirectly depending on the context (Costa & McCrae, 2011; Jensen-Campbell & Malcolm, 2007; McCrae, 1996). More specifically, these traits may shape factors, such as how openly one engages in interactions or how reliable one is with interpersonal commitments. Similarly, as per their conceptualization (McCrae & Costa, 2010), some personality *facets*—the more narrowly defined personality traits that fall below the broader domains—also appear to be inherently interpersonal, whereas others may only relate to interpersonal functioning in specific contexts. A detailed grouping of trait domains and facets within the FFM based on their relationship to interpersonal functioning can be found in Table 1. Unfortunately, despite decades of research that has advanced our understanding of these conceptual targets of interpersonal functioning, we know little about how they may be associated with one's ability to regulate behavior, specifically from a neurocognitive perspective. Two important questions arise in this regard: Is cognitive control related to interpersonally relevant trait domains and the corresponding facets, and are these associations within trait domains similar or different across the underlying facets?

Defining cognitive control

It is important to recognize that the notion of regulating behavior to achieve desirable outcomes has been conceptualized in numerous ways across various theoretical and experimental frameworks (Alvarez & Emory, 2006; Baumeister & Vohs, 2004; Berkman et al., 2017; Hoyle, 2010; Inzlicht et al., 2021; Lezak et al., 2012; Vohs & Finkel, 2006). In the context of this conceptual diversity, the Research Domain Criteria (RDoC) initiative, a neuroscience-based research framework introduced by the National Institute of Mental Health (NIMH), provides an alternative, and arguably more comprehensive, conceptualization of one's ability to engage in behavioral regulation for optimal goal achievement (Insel et al., 2010; National Institute of Mental Health, n.d.-a). Within the RDoC framework, regulatory processes implemented in the service of goal-directed behaviors are subsumed under the broader construct of cognitive control, which is conceptualized as a multifaceted, higher-order construct comprised of several subconstructs through which specific regulatory processes are implemented for achieving goal-directed behaviors. Specifically, *goal selection, updating, representation, and maintenance* (GS), and separately, *response selection, and inhibition/suppression* (RS), are considered under the RDoC framework as two distinct mechanisms (or subconstructs) that subserve cognitive control.[1] Within this context, GS is typically operationalized by behavioral paradigms, such as task-switching/set-shifting

[1] Note that although *performance monitoring* is also proposed as a subconstruct of cognitive control within the RDoC, it is beyond the scope of this paper.

Table 1 List of personality trait domains and their constituting facets as described by the Five Factor Model of personality, with inherently interpersonal traits and facets indicated in boldface[a]

Trait Domain/Facet	Brief Description of Trait/Facet[b]
Agreeableness (A)	Overall tendency to view and engage with others in a favourable manner.
A1: Trust	Tendency to perceive others as well-intentioned.
A2: Straightforwardness	Propensity to be direct and sincere in interpersonal interactions.
A3: Altruism	Inclination to be concerned about the welfare of others.
A4: Compliance	Tendency to capitulate to others, in the context of interpersonal conflict.
A5: Modesty	Propensity to be modest or humble.
A6: Tender-Mindedness	Inclination to be sympathetic towards others.
Extraversion (E)	Overall level of sociability and preference for social interaction.
E1: Warmth	Propensity to be affectionate and friendly.
E2: Gregariousness	The level of preference for interpersonal involvement.
E3: Assertiveness	Inclination to be socially dominant.
E4: Activity	Tendency to be active and have a high level of energy.
E5: Excitement-Seeking	Inclination to pursue stimulation and exciting experiences.
E6: Positive Emotion	Propensity to experience positive affective states.
Neuroticism (N)	Overall susceptibility to psychological distress.
N1: Anxiety	Inclination to experience anxiety or nervousness.
N2: Angry Hostility	Propensity to experience anger.
N3: Depression	Inclination to experience depressed mood.
N4: Self-Consciousness	Sensitivity to evaluation by others in social situations.
N5: Impulsiveness	Inability to resist urges and cravings.
N6: Vulnerability	Inability to cope with stressful situations.
Conscientiousness (C)	Overall tendency to engage in self-control-related behaviour.
C1: Competence	The level of perceived ability for effectively managing day-to-day tasks.
C2: Order	Propensity to be neat and organized.
C3: Dutifulness	Inclination to abide by ethical principles and moral obligations.
C4: Achievement Striving	Tendency to be hard-working and be driven by high aspirations.
C5: Self-Discipline	Ability to carry through with tasks, despite obstacles.
C6: Deliberation	Propensity to think carefully before engaging in a behaviour.
Openness (O)	Overall propensity to entertain new ideas and engage in novel experiences.
O1: Fantasy	Tendency to have a vivid imagination.
O2: Aesthetics	The level of appreciation for artistic stimuli.
O3: Feelings	Sensitivity to internal affective states.
O4: Actions	Willingness to engage in novel activities.
O5: Ideas	Tendency to be open-minded.
O6: Values	Readiness to re-evaluate moral or ethical stances.

[a]The classification of trait domains as being predominantly interpersonally was based on Costa and McCrae (2011) and DeYoung et al. (2013), whereas facets were classified as being inherently interpersonal based on their descriptions provided within the NEO-PI-3 Professional Manual (McCrae & Costa, 2010)

[b]Descriptions are adapted from the NEO-PI-3 Professional Manual (McCrae & Costa, 2010)

and tower tasks (National Institute of Mental Health, n.d.-b). Such paradigms broadly assess an individual's ability to evaluate goal states, generate behavioral strategies for achieving said goal states, and adjust such plans based on changing demands so that behavioral goals can be optimally achieved (Ruocco et al., 2014; Stemme et al., 2007; Kiesel et al., 2010). RS is typically operationalized by behavioral paradigms, such as go/no-go, stop signal, Stroop, and flanker tasks (National Institute of Mental Health, n.d.-c). These tasks evaluate an individual's ability to select the most appropriate response in a given context and to inhibit the propensity to select incorrect responses when faced with multiple response options for achieving a goal (Chikazoe, 2010; MacLeod, 1991). Therefore, GS appears to represent regulatory processes that are more deliberate (e.g., figuring out the steps to achieve behavioral goals), whereas RS represents more time-limited or in-the-moment regulatory processes (e.g., enacting planned steps into appropriate behavioral responses) that occur in the service of achieving goal states. This multidimensional nature of cognitive control raises another key question: Do these two subcomponents of cognitive control relate to interpersonal trait domains and their constituent facets in a consistent way?

Identifying neural targets of cognitive control

Motivated behavior relies on an intricate array of neural regions (Dosenbach et al., 2006; Fox et al., 2005). Regulating such behavior, not surprisingly, also requires the complex interplay of various neural systems that perform basic (e.g., perceptual) and higher-order (e.g., integrating across systems) cognitive functions (Dosenbach et al., 2008; Kouneiher et al., 2009; Miller & Wallis, 2009; Swanson, 2000). Accordingly, cognitive control is suggested to be subserved by a network of brain regions that encompasses aspects of prefrontal, temporal, parietal, cingulate and occipital cortices, as well as subcortical regions, such as the caudate, putamen, thalamus, and the cerebellum (Mackie & Fan, 2017; Niendam et al., 2012). As such, while there are many regions, both cortical and subcortical, that have been implicated in cognitive control-related processes, the prefrontal cortex (PFC) has been consistently identified as a crucial brain region necessary for cognitive control (Badre, 2008; Funahashi, 2001; Fuster, 2000; Koechlin & Hyafil, 2007; Logue & Gould, 2014). In this vein, the lateral aspects of the PFC, both dorsally (primarily consisting of the middle and superior frontal gyri) and ventrally (primarily consisting of the inferior frontal gyrus), have especially been highlighted as being crucial for various procedural elements that constitute cognitive control (Petrides, 2005). Therefore, while recognizing that it may function as part of a complex system that involves a network of brain areas, the lateral PFC has served as a key research target that has elucidated neural mechanisms underlying cognitive control function.

Importantly, although both the left lateral PFC (LLPFC) and right lateral PFC (RLPFC) have been implicated in successful cognitive control, a growing body of research has provided important insights into specific mechanisms underlying cognitive control, suggesting a differential pattern of lateralization across its subconstructs. Specifically, cognitive and behavioral processes that constitute RS (e.g., inhibiting a preponent response and the selection of a correct response among distractors) have been consistently linked to the recruitment of the RLPFC to a much higher degree than its contralateral counterpart (Aron et al., 2004; Chikazoe et al., 2007; Swick et al., 2011; Aron et al., 2014; Rodrigo et al., 2014). Conversely, recruitment of the LLPFC has been identified as a more prominent correlate of processes that constitute GS (e.g., planning, updating, and maintaining goal states) compared with the RLPFC (Cazalis et al., 2003; Kaller et al., 2011; Metuki et al., 2012; Ruocco et al., 2014). Therefore, these nuanced patterns of functional recruitment of the lateral PFC during the performance of corresponding cognitive control behavioral tasks provide useful targets that may serve as neural markers that can help to elucidate whether subconstructs of cognitive control (i.e., RS and GS) show distinct relationships across individual differences, especially with regard to interpersonal dispositions.

Link between cognitive control and interpersonal functioning

There is a longstanding acknowledgement that personality traits are "neuropsychological" or "psychobiological" entities that stem from cognitive processes subserved by the brain (Cloninger, 1987; Eysenck, 1963; Fonagy & Higgitt, 1984; Tellegen, 1991). Little is known, however, regarding the specific associations between interpersonally relevant FFM traits and specific cognitive control mechanisms. This is especially the case with regard to (particularly prefrontal) neural correlates, which are used to operationalize specific cognitive control mechanisms. A small number of functional neuroimaging studies have attempted to shed light on the relationship between prefrontal neural correlates of RS and personality trait domains. Based on these studies, some evidence suggests that interpersonal traits may show distinct patterns of recruitment within the lateral PFC during RS-related processes. More specifically, higher levels of N have been linked to lower recruitment of lateral PFC regions during RS; conversely, higher levels of E, A, and C have been associated with greater recruitment of lateral PFC regions during RS (Eisenberger et al., 2005; Sosic-Vasic et al., 2012; Ikeda et al., 2014; Rodrigo et al., 2016). These findings suggest the possibility of a meaningful relationship between RS and interpersonally relevant traits. Specifically, they suggest a propensity for those who possess what are typically considered more favorable interpersonal dispositions (e.g., higher levels of E and A) to more strongly activate brain regions that are essential for important aspects of cognitive control (i.e., RS). To our knowledge, no study to date has examined the relationship between prefrontal correlates of GS and such interpersonal traits. As such, a comprehensive understanding of how interpersonal dispositions may be linked to specific aspects of cognitive control is yet to be established. This is a notable limitation, especially given the multifaceted nature of cognitive control. In addressing this limitation, neural correlates that can be reliably delineated across subconstructs of cognitive control can be especially useful for better understanding these relationships. Accordingly, clarifying the nuanced ways in which cognitive control relates to interpersonal dispositions can in turn further inform how this important cognitive ability is conceptualized in the context of how people navigate their social environments. Furthermore, the possible relationships between aspects of cognitive control and interpersonally relevant facets within the FFM can further delineate the role of cognitive control within the interpersonal context.

Present study

The present study was designed to address a broad research question: Do two key subconstructs of cognitive control relate to interpersonal trait domains and facets in distinct or similar ways? In this vein, the present study attempted to expand on the current, albeit limited, knowledge on the relationship between neural correlates of cognitive control and self-reported interpersonal traits. Specifically, we explored the associations between two subcomponents of cognitive control (i.e., RS and GS) and measured the corresponding hemodynamic response (oxygenated hemoglobin [oxy-Hb]) observed during performance of behavioral tasks intended to assess each cognitive control subconstruct (i.e., relative changes in oxy-Hb that occurred during previously validated cognitive control tasks) and self-reported interpersonal trait domains and facets within the FFM. Based on previous research that used identical neuroimaging paradigms as the ones used in the present study (Rodrigo et al., 2014; Ruocco et al., 2014), regions-of-interest (ROI) within the PFC that have been most robustly associated with each subconstruct of cognitive control were selected for analyses. Specifically, the RLPFC was selected as the ROI for RS, while the LLPFC was selected for GS (see the ROI selection description below for additional details).

In the service of our broad main research question, we had five specific goals. Our first research goal was informed by previous findings examining the link between FFM traits and RS-related neural recruitment. On the other hand, the remaining goals were designed to explore how the associations between the FFM and cognitive control can be further delineated across subconstructs of cognitive control and facets of the FFM. First, we sought to examine whether changes in oxy-Hb during RS are related differently to interpersonal trait domains within the FFM. Based on previous findings (Rodrigo et al., 2016), we hypothesized that activation change within RLPFC during RS would show distinct associations across E, A, and N. Specifically, we anticipated that individuals with higher scores on the more interpersonally favorable traits (i.e., E and A) would be associated with a higher hemodynamic response within the RLPFC during RS, compared with those who report lower levels of these traits. On the other hand, those who report higher levels of N, a trait domain that is thought to be a risk factor for interpersonal dysfunction, were expected to be linked to attenuated recruitment within the RLPFC during RS, compared with those who report lower N. Second, we explored whether the hemodynamic response associated with GS within the LLPFC would be moderated by participants' self-reported levels of E, A, and N. The third goal was to qualitatively explore whether the associations between these interpersonal traits and cognitive control-related neural recruitment represent unique patterns across RS and GS. The fourth goal was to explore the patterns of associations between oxy-Hb change linked to the above cognitive control subconstructs and the lower-order facets within the FFM. Specifically, we examined whether there is distinct within-trait-domain variability in these associations. Notably, a main emphasis was placed on the facets described as inherently interpersonal, as outlined in Table 1. Finally, we sought to explore the associations between cognitive control-subconstruct-related hemodynamic responses and other traits (i.e., C and O) and their constituent facets that may also be relevant to interpersonal functioning, albeit less directly.

Materials and methods

Participants

The present study consisted of undergraduate students from the University of Toronto Scarborough who had no self-reported history of psychiatric or neurological illness. After providing informed consent, participants first completed a self-administered personality assessment, followed by a neuroimaging protocol assessing RS (both procedures are described in more detail below). Based on time availability, a subset of participants were given the option and chose to complete a second neuroimaging protocol that assessed GS. More specifically, whereas data from 267 participants were initially considered, 30 participants were excluded due to failed embedded validity criteria within the personality instrument (McCrae & Costa, 2010; described in the relevant section below). RS data from an additional 21 participants were excluded from analyses to avoid overlap with regard to the RS neuroimaging protocol, as they had completed this task as part of a previously published study (Rodrigo et al., 2016). Therefore, from the overall sample, 216 participants were included in the RS-related analyses presented in the present study, whereas 95 participants (who chose to complete the GS task in addition to the RS task) were included in the subsequent GS-related analyses. Participant characteristics for these two samples can be found in Table 2. Upon completing the study procedures, participants were compensated with either course credit or CAD 10 per each hour of participation. This study was approved by the Social Sciences, Humanities and Education Research Ethics Board at the University of Toronto.

Table 2 Demographic characteristics of participants who were included in the RS- and GS-related analyses

	RS-Task[a]		GS-Task[b]	
	(*N*=216)		(*N*=95)	
Age	19.7	(*SD*=2.8)	19.3	(*SD*=2.6)
Sex				
Female	140	(64.8%)	65	(68.4%)
Male	76	(35.2%)	30	(31.6%)
Handedness				
Right	185	(85.6%)	83	(87.4%)
Left	21	(9.7%)	9	(9.5%)
Ambidextrous	5	(2.3%)	1	(1.1%)
Ethnicity				
South Asian	84	(38.9%)	33	(34.7%)
Chinese	42	(19.4%)	19	(20.0%)
White	22	(10.2%)	13	(13.7%)
Black	16	(7.4%)	5	(5.3%)
Other	47	(21.8%)	23	(24.2%)

[a]Handedness and ethnicity were not available for five participants

[b]Handedness and ethnicity were not available for two participants

Neuroimaging protocols

Functional near infrared spectroscopy (fNIRS), an established and versatile optical neuroimaging technology, has emerged as a more economical alternative to other functional neuroimaging methods, such as functional magnetic resonance imaging (fMRI). This neuroimaging method provides several advantages that make it ideal for individual differences research, particularly making it an ideal choice for assessing large samples of participants within the context of personality and social neuroscience (Burns & Lieberman, 2019; Di Domenico et al., 2019). Accordingly, in the present study, fNIRS was implemented using the fNIR Imager 1000® (fNIR Devices, Potomac, MD), a 16-channel continuous-wave fNIRS system.

fNIRS procedure

Participants completed the neuroimaging protocol in a dimly lit room by interacting with a stimulus presentation computer with a mouse and keyboard, while the hemodynamic response within the PFC was monitored. Specifically, raw light intensities of light at 730-nm and 850-nm wavelengths were continuously measured with a frequency of 2 Hz and a measurement depth of 1.25 cm (Ayaz et al., 2012). Prior to positioning the fNIRS sensor pad, participants' foreheads were cleaned with an alcohol swab to minimize residue (e.g., cosmetics or sweat). The sensor pad was then positioned on the forehead and was held in place with Velcro® straps. The sensor pad positioning corresponded to the standard electrode positions F7, FP1, FP2, and F8 on the international 10-20 system (as described by Jasper, 1958) and therefore captured hemodynamic activity in Brodmann areas 9, 10, 45, and 46 (Ruocco et al., 2010). Participants then completed one or both of the cognitive tasks described below. During these cognitive tasks, an experimenter was seated quietly behind the participant to monitor the fNIRS equipment and data acquisition process.

fNIRS signal processing

fNIRS signal processing was performed by using the fNIRSoft® Professional Edition software package (Ayaz et al., 2010, 2006). A low-pass filter (linear phase filter with an order of 20 and a cutoff frequency of 0.1 Hz) was applied to address possible high-frequency noise and physiological artifacts in the raw light intensities that were recorded (Izzetoglu et al., 2005; Ayaz et al., 2012). This was followed by a sliding-window motion artifact rejection algorithm for excluding data segments with signal distortions resulting from motion-related probe uncoupling and oversaturation or undersaturation of channels (Ayaz et al., 2010). Activation segments in the resulting refined data were demarcated based on time synchronization markers that were received during cognitive task completion. Relative changes in concentrations of oxy-Hb were then extracted for these activation blocks across the 16 channels (Ayaz et al., 2012).

Assessing RS

RS was operationalized using the Scarborough Non-Affective Go/No-Go Task (SNAG; for detailed task parameters, see Rodrigo et al., 2014). Briefly, the SNAG is a standard motor response control task that instructs participants to provide a response (i.e., button press on a keyboard) to Go stimuli (i.e., a green circle) and then withhold that response to No-Go stimuli (i.e., a red circle) that are presented on a computer monitor. Accordingly, the task was comprised of three blocks that consisted solely of Go stimuli (for the purpose of provoking a prepotent response). Each of these homogenous blocks was followed by mixed blocks that contained pseudo-random combinations of both Go and No-Go stimuli (which pseudo-randomly required participants to withhold their prepotent response). Specifically, each mixed block consisted of 10 Go and 10 No-Go trials (with a total duration of 110 s), with a jittered crosshair fixation between trials to discourage anticipatory responding. Therefore, these mixed blocks represented cognitive processes underlying the cognitive control subconstruct of RS (i.e., selecting a response based on the presented stimulus/inhibiting a prepotent response). Hemodynamic changes during these mixed blocks were contrasted with their local baselines (i.e., first

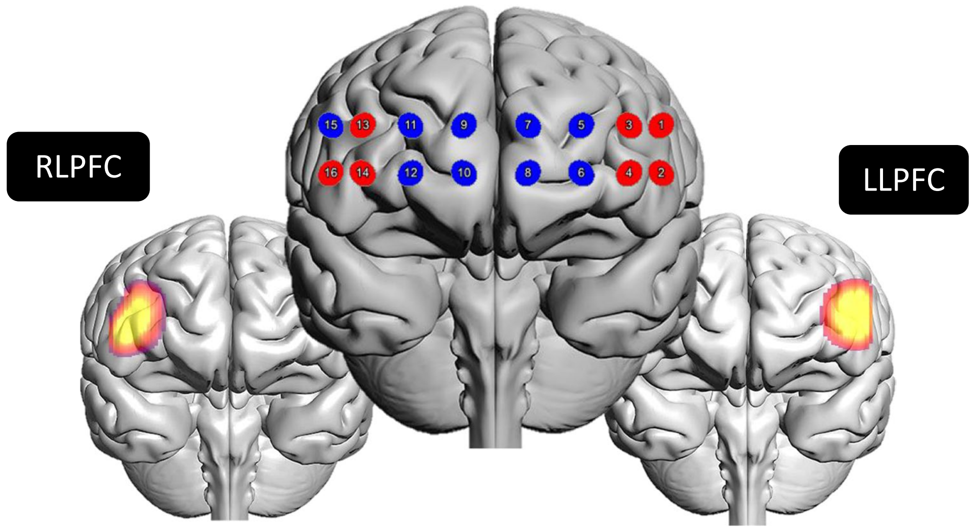

Fig. 1 A template of the prefrontal cortex depicting the 16 fNIRS optodes. Optodes that constituted the ROIs, based on previous neuroimaging findings (Rodrigo et al., 2014; Ruocco et al., 2014), are marked in red. Specifically, optodes 1, 2, 3, and 4 constituted the LLPFC and optodes 13, 14, and 16 constituted the RLPFC

10 s of each block; Rodrigo et al., 2014) to represent RS in subsequent analyses.

Assessing GS

GS was operationalized using the Scarborough Adaptation of the Tower of London task (S-TOL; for detailed task parameters, see Ruocco et al., 2014). In brief, the S-TOL consisted of two task conditions: zero-move (ZM) and multiple-move (MM) conditions. Five alternating blocks of each condition were separated with a 30 s rest period. During the MM condition, participants were presented with two tower configurations (i.e., initial and target) on a computer monitor. They were then asked to mentally calculate the number of moves that would be required to achieve the target configuration from the initial state within 7 s. They were then given 3 s to select either "yes" or "no" to the following question: "Could it be done in exactly two moves?" The MM condition consisted of pseudo-random combinations of either two-move or three-move stimuli to discourage random responding. On the other hand, the ZM condition consisted of 7 s stimuli depicting two identical tower configurations (therefore, requiring zero moves to solve) and the participants were given 3 s to respond to the same question following each stimulus. Both block types consisted of 20 stimuli. Hemodynamic change during the MM blocks were contrasted with the ZM blocks to represent GS in subsequent analyses.

fNIRS ROI selection

The extracted time-series of oxy-Hb concentrations across individual channels were averaged to form RS- and GS-specific ROIs within the PFC. As previously stated, these ROIs were determined based on previous research that investigated these constructs using fNIRS and validated the experimental paradigms that were used in the present study. Specifically, as demonstrated by Rodrigo et al. (2014), RS was associated with increased hemodynamic activity within the anterior aspects of the right inferior and middle frontal gyri (i.e., lateral aspect of Brodmann area 10 and anterior aspects of Brodmann areas 45 and 46). To be consistent with this finding, the RS-related ROI in the present study was demarcated to consist of optode positions/channels 13, 14, and 16 and will be referred to as RLPFC for simplicity. The GS-related ROI was selected based on results from Ruocco et al. (2014), which demonstrated increased hemodynamic activity within the anterior aspects of the left inferior and middle frontal gyri (i.e., lateral aspect of Brodmann area 10 and anterior aspects of Brodmann areas 45 and 46). In line with this finding, the GS-related ROI in the present study was demarcated to consist of optode positions/channels 1, 2, 3, and 4 and will be referred to as LLPFC for simplicity. Figure 1 outlines these ROIs for RS and GS on a standardized brain surface.

Assessment of interpersonal traits and facets

Personality traits and facets were assessed using the NEO-Personality Inventory-3 (NEO-PI-3; McRae, Costa, & Martin, 2005). The NEO-PI-3 consists of 240 items rated on a Likert scale (*Strongly Disagree* = 0 to *Strongly Agree* = 4) and provides individual scores for five traits and six facets for each trait (summarized in Table 1). Trait and facet scores were calculated using the NEO Software System (Costa et al., 2010), which also evaluated the validity of each generated personality profile. Specifically, validity of a given profile was determined by the scoring software based on the presence of nay-saying, acquiescence, missing responses, random responding, and the responses to items assessing participant-reported validity (McRae,

Table 3 Correlations and descriptive statistics of FFM trait domains for participants included in the RS analyses (*N*=216). (The correlations and descriptive statistics for the participants that were included in the GS analyses (*N*=95) are indicated within parentheses)

Personality trait	*M*	*SD*	1	2	3	4	5
1. Neuroticism	16.41 (16.50)	4.13 (4.31)	*0.93 (0.93)*				
2. Extraversion	18.28 (18.14)	3.65 (3.90)	-0.27 (-0.34)	*0.82 (0.84)*			
3. Openness	19.59 (19.95)	3.16 (3.33)	-0.01 (-0.11)	0.26 (0.32)	*0.87 (0.88)*		
4. Agreeableness	18.89 (18.88)	3.33 (3.01)	-0.07 (0.10)	0.05 (-0.04)	0.17 (0.16)	*0.89 (0.86)*	
5. Conscientiousness	18.55 (18.35)	3.84 (3.88)	-0.48 (-0.50)	0.30 (0.28)	0.14 (0.20)	0.10 (-0.002)	*0.93 (0.93)*

Cronbach's alpha for each trait domain is listed along the main diagonal. Correlations above 0.14 are statistically significant at $p<.05$. Correlations above 0.20 and below -0.27 are statistically significant at $p<.01$. (For correlations in parentheses, values above 0.28 and below -0.34 are statistically significant at $p<.01$.)

Table 4 Correlations and descriptive statistics of the FFM trait domain Neuroticism and its constituent facets for participants included in the RS analyses (*N*=216). (The correlations and descriptive statistics for the participants that were included in the GS analyses (*N*=95) are indicated within parentheses)

Trait/Facet	*M*	*SD*	1	2	3	4	5	6	7
1. Neuroticism	16.41 (16.50)	4.13 (4.31)	*0.93 (0.93)*						
2. Anxiety (N1)	18.28 (17.89)	5.58 (5.97)	0.82 (0.85)	*0.77 (0.81)*					
3. Angry Hostility (N2)	14.63 (14.19)	5.21 (4.99)	0.69 (0.66)	0.43 (0.44)	*0.75 (0.74)*				
4. Depression (N3)	17.23 (17.65)	5.89 (6.03)	0.80 (0.83)	0.59 (0.63)	0.44 (0.41)	*0.80 (0.81)*			
5. Self-Consciousness (N4)	17.26 (17.59)	5.17 (5.38)	0.79 (0.80)	0.59 (0.65)	0.44 (0.38)	0.63 (0.68)	*0.68 (0.71)*		
6. Impulsiveness (N5)	16.99 (16.96)	4.12 (4.02)	0.69 (0.69)	0.51 (0.50)	0.49 (0.45)	0.47 (0.51)	0.43 (0.48)	*0.54 (0.51)*	
7. Vulnerability (N6)	14.08 (14.71)	5.54 (5.73)	0.82 (0.85)	0.68 (0.71)	0.48 (0.56)	0.63 (0.66)	0.58 (0.59)	0.49 (0.56)	*0.82 (0.82)*

Cronbach's alpha for the trait domain and its facets are listed along the main diagonal. Correlations above 0.43 are statistically significant at $p<.01$. (For correlations in parentheses, values above 0.38 are statistically significant at $p<.01$)

Costa, & Martin, 2005). Accordingly, participants whose personality profiles were flagged as questionable by the scoring software based on their response patterns were excluded from subsequent analyses. Descriptive statistics and correlations among the traits for participants included in RS-related analyses ($N = 216$) and in GS-related analyses ($N = 95$) are presented in Table 3. Descriptive statistics and correlations for facets and their respective trait domains across both RS and GS samples are subsequently presented in Tables 4, 5, 6, 7 and 8. No differences were found between the smaller group of participants who completed both neuroimaging tasks ($N = 95$) and the larger group of participants who just completed the RS task ($N = 216$) with regard to their personality trait or facet scores ($|t(235)|s \leq 2.12$, *FDR-corrected p*s ≥ 0.99, $|d|s \leq 0.28$).

Data analytic approach

The aggregated fNIRS time-series data for each ROI were analyzed using multilevel models (Snijders and Bosker, 2011) and implemented in IBM SPSS Statistics (Versions 26 and 27; Armonk, NY). Specifically, the time-series of oxy-Hb measurements for each ROI were nested within participants (for RS, a total of 304, 757 observations were nested within 216 participants; for GS, a total of 111, 788 observations were nested within 95 participants). All models were estimated using the restricted maximum likelihood approach, an unstructured covariance matrix, and the Satterthwaite method of estimating degrees of freedom. First, we estimated two models that examined the Level 1 within-person effect of RS and GS on relative changes in oxy-Hb within the respective ROIs in order to confirm the suitability of the selected ROIs (i.e., a significant hemodynamic change from baseline). Specifically, within these models, RS and GS were coded as 0.5, whereas their respective baseline conditions were coded as −0.5, so that the reported coefficients represent the change in oxy-Hb (μmol/l) from baseline to cognitive control-task condition. We then estimated models consisting of the Level 1 within-person effect of cognitive control, the Level 2 between-person effect of each Interpersonal Trait/Facet, and the Cognitive Control × Interpersonal Trait/Facet cross-level interaction. A separate set of analyses was conducted for each personality trait domain or facet corresponding to each previously identified ROI for RS and GS.

Table 5 Correlations and descriptive statistics of the FFM trait domain Extraversion and its constituent facets for participants included in the RS analyses (*N*=216). (The correlations and descriptive statistics for the participants that were included in the GS analyses (*N*=95) are indicated within parentheses)

Trait/Facet	*M*	*SD*	1	2	3	4	5	6	7
1.Extraversion	18.28 (18.14)	3.65 (3.90)	*0.82 (0.84)*						
2. Warmth (E1)	21.56 (21.82)	4.39 (4.19)	0.75 (0.75)	*0.69 (0.68)*					
3. Gregariousness (E2)	17.06 (16.26)	5.83 (5.65)	0.75 (0.79)	0.60 (0.62)	*0.78 (0.74)*				
4. Assertiveness (E3)	16.12 (15.92)	5.52 (5.85)	0.67 (0.73)	0.39 (0.44)	0.34 (0.52)	*0.80 (0.83)*			
5. Activity (E4)	15.93 (15.71)	4.19 (4.46)	0.57 (0.64)	0.26 (0.31)	0.26 (0.46)	0.42 (0.50)	*0.58 (0.64)*		
6. Excitement Seeking (E5)	19.38 (19.35)	5.07 (5.35)	0.61 (0.68)	0.29 (0.33)	0.47 (0.42)	0.30 (0.44)	0.27 (0.46)	*0.64 (0.68)*	
7. Positive Emotion (E6)	19.64 (19.81)	5.68 (5.90)	0.73 (0.71)	0.64 (0.63)	0.43 (0.44)	0.38 (0.36)	0.34 (0.30)	0.24 (0.34)	*0.80 (0.82)*

Cronbach's alpha for the trait domain and its facets are listed along the main diagonal. Correlations above 0.24 are statistically significant at $p<.01$. (For correlations in parentheses, values above 0.30 are statistically significant at $p<.01$)

Table 6 Correlations and descriptive statistics of the FFM trait domain Agreeableness and its constituent facets for participants included in the RS analyses (*N*=216). (The correlations and descriptive statistics for the participants that were included in the GS analyses (*N*=95) are indicated within parentheses)

Trait/Facet	*M*	*SD*	1	2	3	4	5	6	7
1.Agreeableness	18.89 (18.88)	3.33 (3.01)	*0.89 (0.86)*						
2. Trust (A1)	16.54 (21.82)	4.97 (4.19)	0.52 (0.47)	*0.77 (0.78)*					
3. Straightforwardness (A2)	17.53 (16.26)	5.05 (5.65)	0.74 (0.74)	0.26 (0.25)	*0.71 (0.62)*				
4. Altruism (A3)	22.68 (15.92)	4.29 (5.85)	0.74 (0.69)	0.35 (0.26)	0.48 (0.50)	*0.73 (0.68)*			
5. Compliance (A4)	16.02 (15.71)	5.02 (4.46)	0.61 (0.68)	0.31 (0.30)	0.39 (0.41)	0.37 (0.37)	*0.71 (0.63)*		
6. Modesty (A5)	18.39 (19.35)	5.80 (5.35)	0.62 (0.59)	0.03 (-0.08)	0.48 (0.37)	0.29 (0.28)	0.26 (0.28)	*0.83 (0.79)*	
7. Tender-Mindedness (A6)	22.16 (19.81)	4.53 (5.90)	0.62 (0.66)	0.19 (0.66)	0.30 (0.09)	0.51 (0.35)	0.16 (0.42)	0.37 (0.27)	*0.71 (0.67)*

Cronbach's alpha for the trait domain and its facets are listed along the main diagonal. Correlations above 0.16 are statistically significant at $p<.05$. Correlations above 0.26 are statistically significant at $p<.01$. (For correlations in parentheses, values above 0.25 are statistically significant at $p<.05$. Correlations above 0.26 are statistically significant at $p<.01$)

Table 7 Correlations and descriptive statistics of the FFM trait domain Conscientiousness and its constituent facets for participants included in the RS analyses (*N*=216). (The correlations and descriptive statistics for the participants that were included in the GS analyses (*N*=95) are indicated within parentheses)

Trait/Facet	*M*	*SD*	1	2	3	4	5	6	7
1.Conscientiousness	18.55 (18.35)	3.84 (3.88)	*0.93 (0.93)*						
2. Competence (C1)	19.00 (18.96)	4.56 (4.83)	0.78 (0.77)	*0.72 (0.75)*					
3. Order (C2)	17.72 (17.55)	5.29 (5.57)	0.64 (0.59)	0.33 (0.28)	*0.78 (0.81)*				
4. Dutifulness (C3)	20.59 (20.43)	4.08 (3.99)	0.75 (0.79)	0.52 (0.60)	0.39 (0.34)	*0.63 (0.59)*			
5. Achievement Striving (C4)	19.18 (18.98)	5.56 (5.12)	0.79 (0.75)	0.57 (0.53)	0.41 (0.37)	0.53 (0.51)	*0.84 (0.79)*		
6. Self-Discipline (C5)	17.07 (16.88)	5.72 (5.88)	0.82 (0.79)	0.60 (0.58)	0.40 (0.38)	0.54 (0.51)	0.71 (0.63)	*0.82 (0.83)*	
7. Deliberation (C6)	17.76 (17.29)	4.70 (5.33)	0.67 (0.71)	0.62 (0.59)	0.33 (0.32)	0.50 (0.63)	0.33 (0.33)	0.42 (0.37)	*0.74 (0.81)*

Cronbach's alpha for the trait domain and its facets are listed along the main diagonal. Correlations above 0.33 are statistically significant at $p<.01$. (For correlations in parentheses, values above 0.28 are statistically significant at $p<.01$)

Within these models, the cognitive control activation contrasts were effect-coded as described above, whereas the raw trait or facet scores from the NEO-PI-3 were grand-mean centered. The presented results focus primarily on the Cognitive Control × Interpersonal Trait/Facet cross-level interaction in each model, which examined how within-person

Table 8 Correlations and descriptive statistics of the FFM trait domain Openness and its constituent facets for participants included in the RS analyses (N=216). (The correlations and descriptive statistics for the participants that were included in the GS analyses (N=95) are indicated within parentheses)

Trait/Facet	*M*	*SD*	1	2	3	4	5	6	7
1.Openness	19.59 (19.95)	3.16 (3.33)	*0.87 (0.88)*						
2. Fantasy (O1)	19.66 (19.64)	4.85 (4.82)	0.58 (0.61)	*0.71 (0.71)*					
3. Aesthetics (O2)	18.94 (19.59)	5.98 (6.22)	0.68 (0.69)	0.23 (0.28)	*0.79 (0.83)*				
4. Feelings (O3)	20.35 (20.37)	4.53 (4.92)	0.66 (0.66)	0.33 (0.33)	0.38 (0.33)	*0.69 (0.76)*			
5. Actions (O4)	16.39 (17.19)	3.77 (3.97)	0.53 (0.58)	0.14 (0.25)	0.30 (0.27)	0.30 (0.31)	*0.53 (0.58)*		
6. Ideas (O5)	20.57 (21.12)	5.83 (6.19)	0.71 (0.74)	0.28 (0.36)	0.37 (0.41)	0.30 (0.36)	0.27 (0.38)	*0.85 (0.85)*	
7. Values (O6)	21.65 (21.82)	4.62 (4.41)	0.67 (0.62)	0.34 (0.31)	0.26 (0.29)	0.36 (0.34)	0.34 (0.36)	0.43 (0.35)	*0.69 (0.65)*

Cronbach's alpha for the trait domain and its facets are listed along the main diagonal. Correlations above 0.23 are statistically significant at p<.05. Correlations above 0.14 are statistically significant at p<.01. (For correlations in parentheses, values above 0.25 are statistically significant at p<.05. Correlations above 0.27 are statistically significant at p<.01)

differences in cognitive control-related neural activity may systematically vary based on between-person differences in each interpersonal trait domain or facet. As outlined by Aiken et al. (1991), we then examined the simple effects of domains or facets on the hemodynamic response associated with each subconstruct of cognitive control. Specifically, the presented results focus on the simple effects of high (i.e., one standard deviation [SD] above the mean) and low (i.e., one SD below the mean) levels of each domain or facet on hemodynamic change associated with each subconstruct of cognitive control (i.e., change in oxy-Hb from baseline). These results are summarized below, and further details are provided in supplementary materials. The simple effects of each domain or facet on overall hemodynamic activation during the baseline condition and during RS or GS conditions were explored and are included in the supplementary materials. To control for family-wise Type I error, the False Discovery Rate approach was used across each set of analyses that represented a trait domain or a facet (Benjamini & Hochberg, 1995; Benjamini & Yekutieli, 2001). Accordingly, the reported p-values were corrected for multiple comparisons and are presented along with semi-partial R-squared (R_β^2) as a measure of effect size (Edwards et al., 2008).

Results

Behavioral performances

Response selection

Consistent with the design of the go/no-go behavioral task (SNAG), which was intended to yield near-ceiling levels of accuracy (Rodrigo et al., 2014), participants demonstrated a high level of accuracy during RS (i.e., the sum of correct responses to Go and No-Go stimuli during mixed blocks; M = 96.00%, SD = 3.92%). Spearman correlational analyses revealed no associations between task accuracy and personality trait domains (|r|s < 0.08, uncorrected ps > 0.05). Significant correlations, however, were observed between task accuracy and the facets of Activity (E4; r = −0.15, uncorrected p < 0.05), Dutifulness (C3; r = 0.14, uncorrected p < 0.05), and Deliberation (C6; r = 0.14, uncorrected p < 0.05). No other significant correlations were observed between accuracy on the RS behavioral task and personality facets (|r|s < 0.08, uncorrected ps > 0.05).

Goal selection

As anticipated according to the design of the GS task (S-TOL; Ruocco et al., 2014), participants also demonstrated a high level of accuracy during GS (i.e., total number of correct MM trials; M = 92.16%, SD = 11.08%). Similar to RS, Spearman correlations revealed no significant associations between task accuracy during GS and personality trait domains (|r|s < 0.08, uncorrected ps > 0.05). Significant correlations, however, were observed between task accuracy and the following facets: Trust (A1; r = 0.24, uncorrected p < 0.05), Dutifulness (C3; r = 0.20, uncorrected p < 0.05), and Deliberation (C6; r = 0.23, uncorrected p < 0.05). No other correlations were observed between accuracy during GS and personality facets (|r|s < 0.10, uncorrected ps > 0.05). With regard to reaction time on the task (M = 901.22 ms, SD = 167.31 ms), with the exception of Actions (O4; r = −0.30, uncorrected p < 0.01), no significant Spearman correlations were found with trait domains or their constituent facets ((|r|s < 0.21, uncorrected ps > 0.05).

Neuroimaging results

Response selection

Consistent with previous findings (Rodrigo et al., 2014, 2016), RS was associated with increased hemodynamic

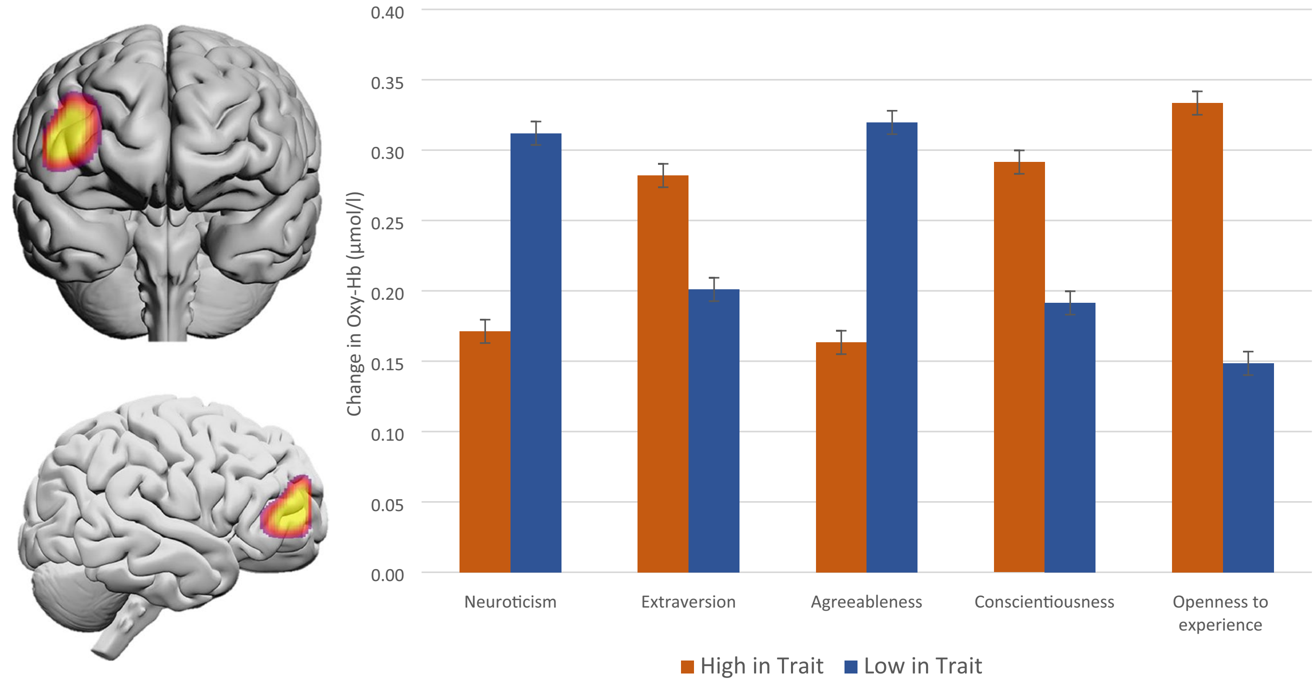

Fig. 2 Response selection-related hemodynamic response within the right lateral prefrontal cortex for high (+1SD) and low (-1SD) levels of all trait domains. Only the hemodynamic responses that correspond to simple effects of statistically significant RSxTrait interactions are displayed. All displayed hemodynamic responses are significantly different from zero (FDR-corrected $ps<.001$)

activation within the RLPFC ($b = 0.24$, $p < 0.001$, $R_\beta^2 = 0.0055$). These results indicate that there was a 0.24 µmol/l increase in oxy-Hb from baseline, within the RLPFC, when participants engaged in RS.

RS × Trait Interactions Significant cross-level interactions were found for all three interpersonal trait domains (N: $b = -0.02$, $p < 0.001$, $R_\beta^2 = 0.0005$; E: $b = 0.01$, $p < 0.001$, $R_\beta^2 = 0.0002$; A: $b = -0.02$, $p < 0.001$, $R_\beta^2 = 0.0006$), as well as for C and O (C: $b = 0.01$, $p < 0.001$, $R_\beta^2 = 0.0002$; O: $b = 0.03$, $p < 0.001$, $R_\beta^2 = 0.0008$), within the RLPFC ROI. When examining the simple effects of traits on hemodynamic change associated with RS (i.e., change in oxy-Hb from baseline to RS), significant differences were seen across high and low levels of traits. Specifically, high (i.e., 1 SD above the mean) N was associated with significantly attenuated hemodynamic activity within the ROI ($b = 0.17$, $p < 0.001$, $R_\beta^2 = 0.0014$) compared with low (i.e., 1 SD below the mean) N ($b = 0.31$, $p < 0.001$, $R_\beta^2 = 0.0046$). Similarly, high A also was associated with a lower increase in oxy-Hb during RS ($b = 0.16$, $p < 0.001$, $R_\beta^2 = 0.0013$) compared with low A ($b = 0.32$, $p < 0.001$, $R_\beta^2 = 0.0048$). High E, on the other hand, was linked to a higher activation increase within the ROI ($b = 0.28$, $p < 0.001$, $R_\beta^2 = 0.0038$), whereas lower E was linked to lower activation change ($b = 0.20$, $p < 0.001$, $R_\beta^2 = 0.0019$). Similar to E, high C was linked to significantly increased activation within the RLPFC ($b = 0.29$, $p < 0.001$, $R_\beta^2 = 0.0040$), whereas low C was linked to attenuated activation when engaging in RS ($b = 0.19$, $p < 0.001$, $R_\beta^2 = 0.0017$). Low O also was associated with reduced activation change ($b = 0.15$, $p < 0.001$, $R_\beta^2 = 0.0010$) compared with high O ($b = 0.33$, $p < 0.001$, $R_\beta^2 = 0.0053$). These results are detailed in Supplementary Table 1. The activation change associated with RS (from baseline to task condition) across high and low levels of all trait domains are depicted in Fig. 2.

RS × Facet Interactions Significant cross-level interactions were found for all six facets of N ($|b|s > 0.00$, $ps < 0.05$, $R_\beta^2s > 0.00002$) and A ($|b|s > 0.01$, $ps < 0.001$, $R_\beta^2s > 0.0002$), whereas four of the six facets of E—Gregariousness (E2), Assertiveness (E3), Activity (E4), and Excitement-Seeking (E5)—also demonstrated significant interactions ($|b|s > 0.01$, $ps < 0.001$, $R_\beta^2s > 0.0001$). Additionally, all six facets of O ($|b|s > 0.00$, $ps < 0.01$, $R_\beta^2s > 0.0001$), and all facets of C, except for Self-Discipline (C5; $b < 0.01$, $p = 0.35$, $R_\beta^2 < 0.0001$), also demonstrated significant interactions ($|b|s > 0.004$, $ps < 0.001$, $R_\beta^2s > 0.00004$).

Variability was apparent across facets under the trait domains when probing the simple effects of high and low levels of these facets on RS-related activation change within the RLPFC (Supplementary Tables 2-6). Specifically, low Self-Consciousness (N4) was associated with attenuated activation within the ROI during RS ($b = 0.22$, $p < 0.001$,

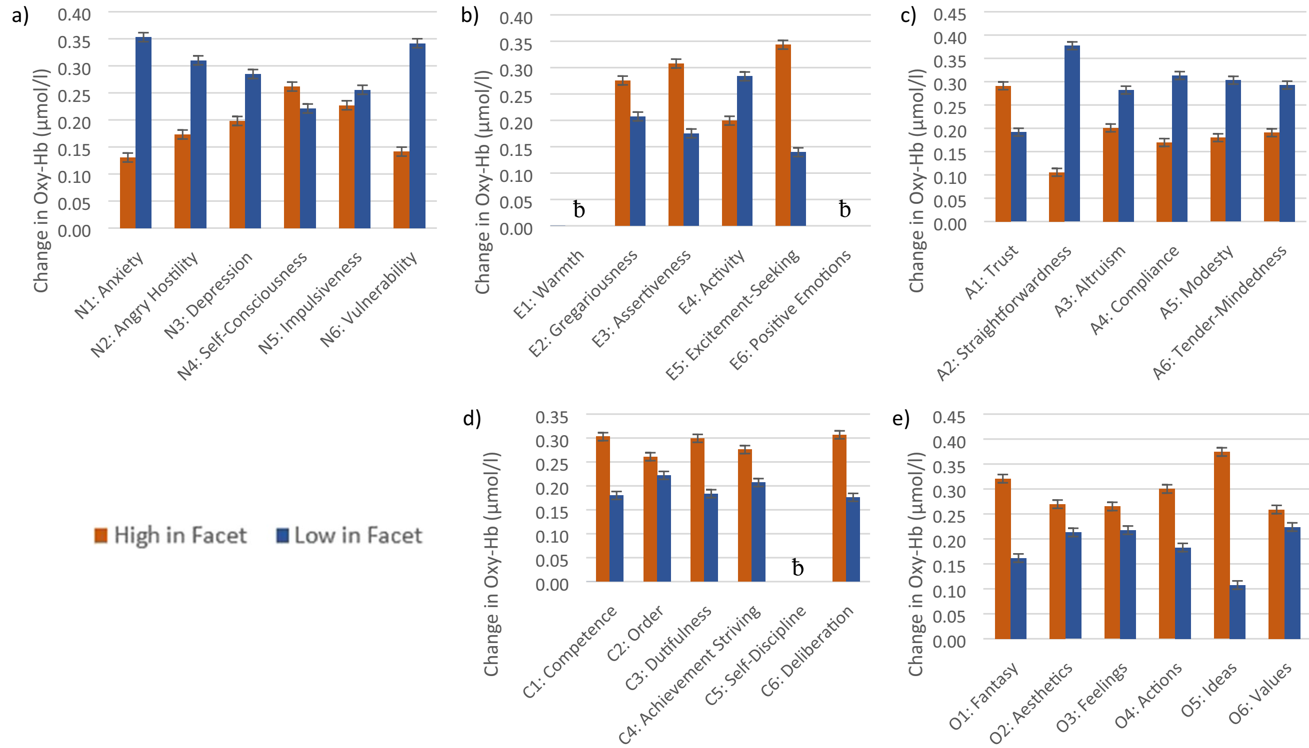

Fig. 3 RS-related hemodynamic response within the RLPFC for high (+1SD) and low (-1SD) levels of facets that constitute **a**) Neuroticism, **b**) Extraversion, **c**) Agreeableness, **d**) Conscientiousness, **e**) Openness. Only the hemodynamic responses that correspond to simple effects of statistically significant RSxFacet interactions are displayed. All displayed hemodynamic responses are significantly different from zero (FDR-corrected *ps*<.001). [b]The Facet x RS interaction was not significant. Therefore, corresponding simple effects were not probed

$R_\beta^2 = 0.0023$) compared with high N4 ($b = 0.26$, $p < 0.001$, $R_\beta^2 = 0.0032$). Conversely, higher levels of all other facets of N were linked to reduced activation change (*bs* ≥ 0.13, *ps* < 0.001, R_β^2s > 0.0008) compared with low levels of those facets (*bs* ≥ 0.22, *ps* < 0.001, R_β^2s > 0.0031). With regard to the facets of E, lower E2, E3, and E5 were associated with attenuated recruitment of the RLPFC (*bs* ≥ 0.14, *ps* < 0.001, R_β^2s > 0.0009) compared with higher levels of these facets (*bs* ≥ 0.28, *ps* < 0.001, R_β^2s > 0.0036). Higher E4, conversely, was linked to lower hemodynamic change within the RLPFC ($b = 0.20$, $p < 0.001$, $R_\beta^2 = 0.0019$) compared with lower E4 ($b = 0.28$ $p < 0.001$, $R_\beta^2 = 0.0038$). Low trust (A1) was associated with reduced activation within the ROI during RS ($b = 0.19$, $p < 0.001$, $R_\beta^2 = 0.0017$) compared with high A1 ($b = 0.29$, $p < 0.001$, $R_\beta^2 = 0.0040$). Higher levels of all other facets of A were associated with lower activation in the ROI (*bs* ≥ 0.11, *ps* < 0.001, R_β^2s > 0.0005) compared with lower levels (*bs* ≥ 0.28, *ps* < 0.001, R_β^2s > 0.0038).

Regarding facets for trait domains less directly related to interpersonal functioning, higher levels of Competence (C1), Order (C2), Dutifulness (C3), Achievement Striving (C4), and Deliberation (C6) were linked to larger increases in oxy-Hb within the ROI (*bs* ≥ 0.26, *ps* < 0.001, R_β^2s > 0.0036) compared with lower levels of these facets (*bs* ≥ 0.18, *ps* < 0.001, R_β^2s > 0.0015). Additionally, lower levels of all facets of O were associated with attenuated recruitment of the RLPFC (*bs* ≥ 0.11, *ps* < 0.001, R_β^2s > 0.0005) compared with higher levels (*bs* ≥ 0.26, *ps* < 0.001, R_β^2s > 0.0032). These results relating to the associations between RS and facets across each trait are depicted in Fig. 3.

Goal selection

Consistent with previous findings (Ruocco et al., 2014), GS was associated with increased hemodynamic activation within the LLPFC ($b = 0.25$, $p < 0.001$, $R_\beta^2 = 0.0005$). These results indicate that there was a 0.25 µmol/l increase in oxy-Hb from baseline, within the LLPFC, when participants engaged in GS.

GS × Trait Interactions Significant cross-level interactions were found for all three interpersonal traits (N: $b = -0.02$, $p < 0.001$, $R_\beta^2 = 0.0005$; E: $b = 0.01$, $p < 0.001$, $R_\beta^2 = 0.0002$; A: $b = -0.02$, $p < 0.001$, $R_\beta^2 = 0.0006$), as well as for C ($b = 0.01$, $p < 0.001$, $R_\beta^2 = 0.0002$), within the LLPFC. The interaction between O and GS, conversely, was not

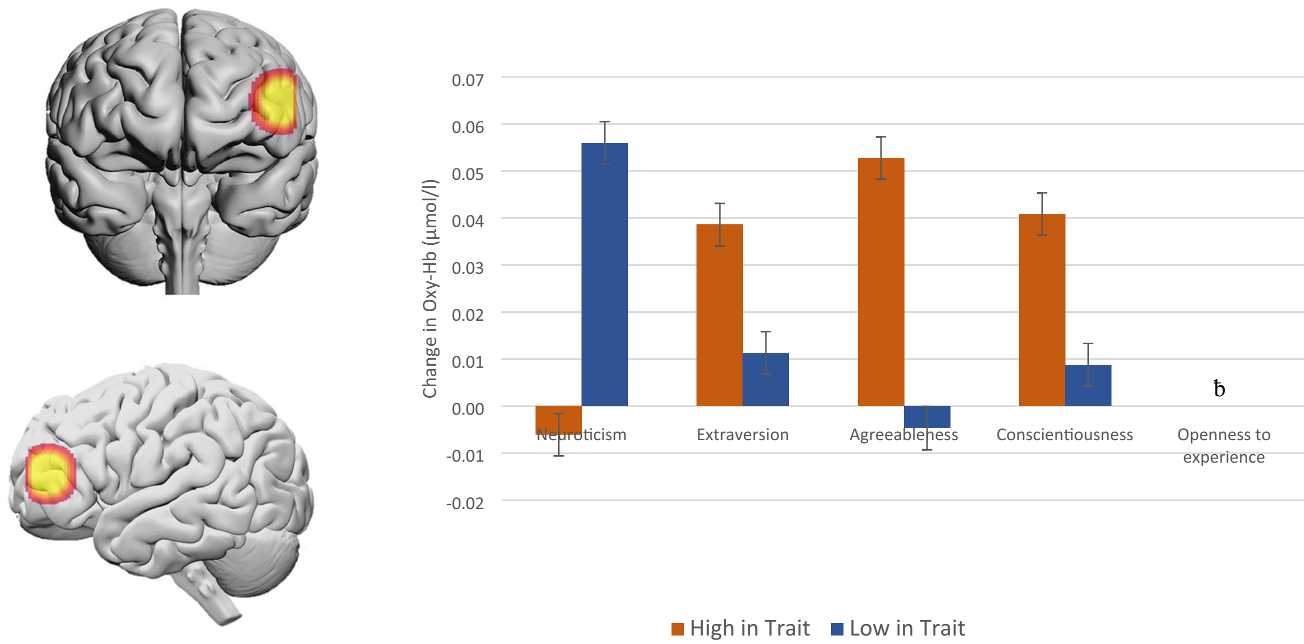

Fig. 4 Goal Selection-related hemodynamic response within the left lateral prefrontal cortex for high (+1SD) and low (-1SD) levels of all trait domains. Only the hemodynamic responses that correspond to simple effects of statistically significant GSxTrait interactions are displayed. All displayed hemodynamic responses are significantly different from zero (FDR-corrected *ps*<.001). [b]The Trait x GS interaction was not significant. Therefore, corresponding simple effects were not probed

significant ($b < 0.01$, $p = 0.28$, $R_{\beta}^2 < 0.0001$). When examining the simple effects of traits on hemodynamic change associated with GS (i.e., change in oxy-Hb from baseline to GS), significant differences were seen across high and low levels of traits. Specifically, lower N was associated with an increase in hemodynamic activity within the LLPFC ($b = -0.06$, $p < 0.001$, $R_{\beta}^2 = 0.0014$) compared with higher N, which was not associated with any change in activity during GS ($b = -0.01$, $p = 0.22$, $R_{\beta}^2 < 0.0001$). Lower E, conversely, was linked to attenuated activation within the ROI ($b = 0.01$, $p < 0.05$, $R_{\beta}^2 < 0.0001$) compared with higher E ($b = 0.04$, $p < 0.001$, $R_{\beta}^2 = 0.0007$). Higher A also was linked to an increase in activation during GS ($b = 0.05$, $p < 0.001$, $R_{\beta}^2 = 0.0012$), whereas lower A was not associated with significant change in activation during GS ($b = -0.00$, $p = 0.34$, $R_{\beta}^2 < 0.0001$). Additionally, similar to A, higher C was associated with increased recruitment of the LLPFC during GS ($b = 0.04$, $p < 0.001$, $R_{\beta}^2 = 0.0007$), whereas lower C was not linked to significant change in activation ($b = 0.01$, $p = 0.07$, $R_{\beta}^2 < 0.0001$). These results are detailed in Supplementary Table 7. The activation changes associated with GS (from baseline to task condition) across high and low levels of all trait domains are and depicted in Fig. 4.

GS × Facet Interactions Significant cross-level interactions were found for all six facets of N ($|b|$s > 0.001, $ps < 0.01$, R_{β}^2s ≥ 0.0001) and A ($|b|$s > 0.003, $ps < 0.01$, R_{β}^2s ≥ 0.0001), while three of the of the six facets of E (E2, E3, and E4) also demonstrated significant interactions ($|b|$s > 0.001, $ps < 0.05$, R_{β}^2s ≥ 0.00005). Additionally, all six facets of C ($|b|$s > 0.002, $ps < 0.01$, R_{β}^2s ≥ 0.0001) and all facets of O ($|b|$s > 0.001, $ps < 0.001$, R_{β}^2s ≥ 0.0003), except for Feelings (O3; $b < -0.01$, $p = 0.16$, $R_{\beta}^2 < 0.0001$), also demonstrated significant interactions.

Variability also was observed when probing the simple effects of high and low levels of these facets on GS-related activation change within the LLPFC (Supplementary Tables 8-12). Specifically, across all facets of N, higher levels of a given facet were associated with either attenuated activity or deactivation (N2 and N4; $bs \leq -0.01$, $ps < 0.05$, R_{β}^2s ≥ 0.00004) or no significant change (N5 and N6; $|b|$s < 0.01, $ps \geq 0.14$, R_{β}^2s < 0.0001) within the RLPFC when engaging in GS. Lower levels of all facets of N were associated with increased recruitment of the ROI ($bs \geq 0.03$, $ps < 0.001$, R_{β}^2s $= 0.0005$). With regard to A, high levels of all facets were linked to increased recruitment of the ROI during GS ($bs \geq 0.04$, $ps < 0.001$, R_{β}^2s $= 0.0008$), with the exception of high Tender-Mindedness (A6; $b = -0.01$, $p = 0.14$, $R_{\beta}^2 < 0.0001$), which was not associated with significant change. Higher levels of all facets of E were linked to increased hemodynamic activation during GS within the ROI ($bs \geq 0.02$, $ps < 0.001$, R_{β}^2s ≥ 0.0003), whereas lower levels of facets of E were linked to attenuated activation (E1, E2, E5, and E6; $bs \geq 0.04$, $ps < 0.001$, R_{β}^2s ≥ 0.0001) or no change in activation (E3 and E4; $bs \leq 0.01$, $ps \geq 0.22$, R_{β}^2s < 0.0001).

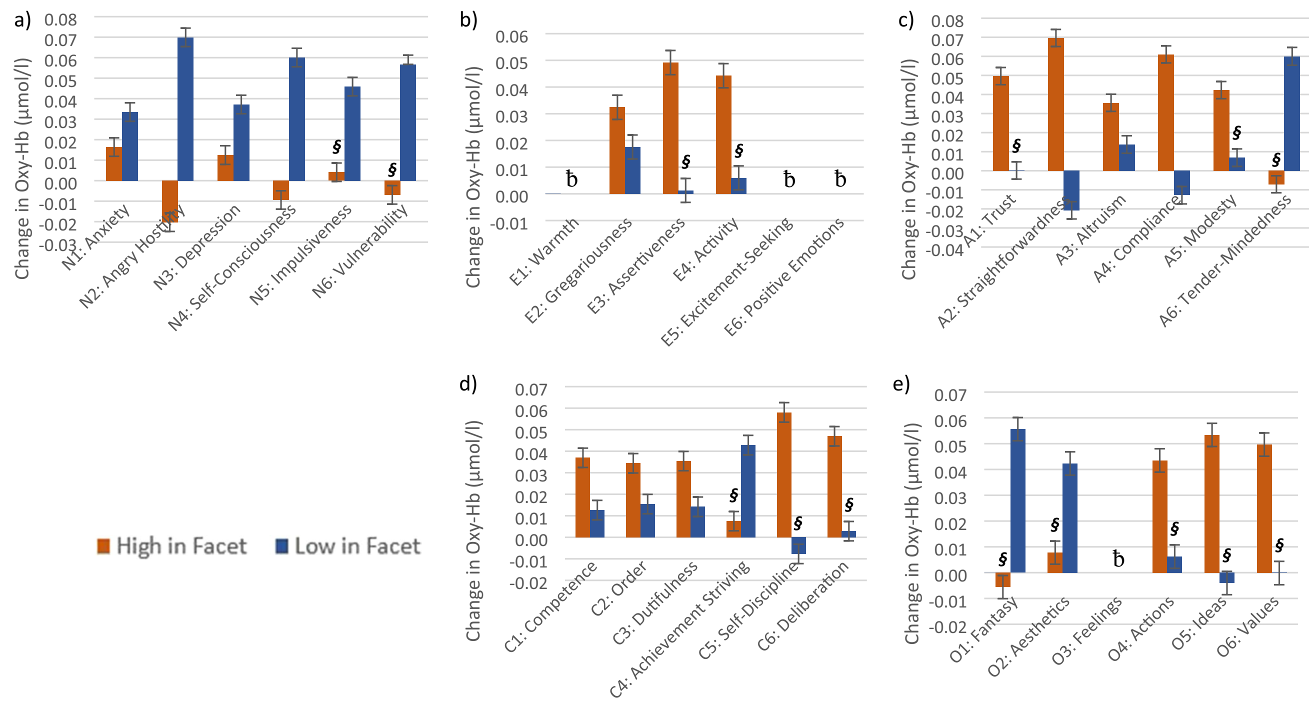

Fig. 5 GS-related hemodynamic response within the RLPFC for high (+1SD) and low (-1SD) levels of facets that constitute **a**) Neuroticism, **b**) Extraversion, **c**) Agreeableness, **d**) Conscientiousness, **e**) Openness. Only the hemodynamic responses that correspond to simple effects of statistically significant GSxFacet interactions are displayed. Unless indicated otherwise, all displayed hemodynamic responses are significantly different from zero (FDR-corrected *ps*<.05). [§]Not significantly different from zero (FDR-corrected *p*>.05). [b]The Facet x GS interaction was not significant. Therefore, corresponding simple effects were not probed

Additionally, except for C4 (low C4: $b = 0.04$, $p < 0.001$, $R_\beta^2 = 0.0008$; high C4: $b = 0.01$, $p = 0.12$, $R_\beta^2 < 0.0001$), lower levels of all other facets of C were linked to attenuated activation (C1, C2, and C3; $bs \geq 0.01$, $ps < 0.01$, $R_\beta^2s = 0.0001$) or no significant change within the ROI (C5 and C6; $|b|s \leq 0.01$, $ps \geq 0.11$, $R_\beta^2s < 0.0001$) compared with higher levels of these facets ($bs \geq 0.03$, $ps < 0.001$, $R_\beta^2s \geq 0.0005$). Lower Fantasy (O1) and Aesthetics (O2) were linked to increased activation ($bs \geq 0.04$, $ps < 0.001$, $R_\beta^2s \geq 0.0008$) compared with higher levels of these facets, which were not associated with significant change within the ROI ($|b|s \leq 0.01$, $ps \geq 0.11$, $R_\beta^2s < 0.0001$). Higher O4, Ideas (O5), and Values (O6), on the other hand, were linked to increased activation within the ROI ($bs \geq 0.04$, $ps < 0.001$, $R_\beta^2s \geq 0.0008$), whereas lower levels of these facets were not linked to significant change ($|b|s \leq 0.01$, $ps \geq 0.22$, $R_\beta^2 < 0.0001$). These results relating to the associations between GS and facets across each trait are depicted in Fig. 5.

Discussion

The present study identified clear associations between cognitive control-related neural responses and interpersonal dispositions. To our knowledge, these results are the first to suggest that key differences may exist regarding how these interpersonal dispositions relate to subcomponents of cognitive control. Some variability was also observed in the patterns of associations between interpersonally relevant facets within the FFM and neural activation during both RS and GS. Specifically, while most interpersonal facets showed similar patterns of associations with their corresponding higher-order trait domains, Self-Consciousness and Trust demonstrated opposite trends for RS, while Tender-Mindedness demonstrated an opposite trend for GS. Therefore, these results also are the first to suggest that a subset of the narrower facets in the FFM share divergent associations with cognitive control-related neural activity compared to the broader interpersonally relevant trait domains within which the facets are subsumed. Finally, while higher levels of both C and O were associated with a stronger hemodynamic response for RS, only C demonstrated a similar pattern of activation for GS, as O was not significantly associated with GS. Notable variability was also seen with regard to the facets that constitute these traits, with some facets demonstrating patterns of activation that were opposite to those linked to their trait domains.

Whereas no trait domain showed a significant association with behavioral performances on the RS or GS tasks, different patterns of association were observed between trait domains and neural activation related to RS and GS within their respective ROIs. In keeping with our hypothesis, higher levels of E were associated with a stronger hemodynamic response within the RLPFC during RS, while high N was linked to an attenuated response within the same ROI. Contrary to our expectation, however, high A also was associated with lower hemodynamic recruitment within the RLPFC during RS. These interpersonal traits also demonstrated significant associations with the neural activation observed within the LLPFC during GS. Specifically, the hemodynamic response patterns during GS associated with both E and N were similar to those observed during RS. On the other hand, neural activation associated with A demonstrated an opposite trend, where higher A was linked to higher hemodynamic recruitment during GS within the ROI.

Neuroticism

Lower N was associated with a higher hemodynamic response within the RLPFC during RS, as compared to the attenuated level of activation associated with higher N. This is largely consistent with previous research, which also has demonstrated a link between N and attenuated PFC recruitment during tasks assessing RS (Rodrigo et al., 2016; Sosic-Vasic et al., 2012). Therefore, this finding contributes to a growing body of neuroimaging evidence suggesting that N may be associated with lower cognitive control-related activation within the PFC (Forbes et al., 2014; Servaas et al., 2015; Xu & Potenza, 2012). Interestingly, however, there were divergences with regard to the associations between RS-related hemodynamic change and the two interpersonally relevant facets of N, which could suggest different underlying neural mechanisms for these facets. Specifically, whereas higher angry hostility (N2) was linked to an attenuated RS-related activation change within the RLPFC, in line with the pattern observed for the broader trait domain, higher self-consciousness (N3) was associated with a stronger hemodynamic response. Although a previous neuroimaging investigation of RS-related processes using fMRI and an alternate questionnaire measuring self-consciousness did not report a significant association between this construct and lateral PFC recruitment (Eisenberger et al., 2005), other neuroimaging evidence suggests that RLPFC in particular may represent an important neural correlate that subserves this construct (Morita et al., 2008). Specifically, in line with its conceptualization within the FFM (i.e., sensitivity to evaluation by interpersonal others), the level of embarrassment experienced during socially evaluative situations was linked to the neural response within the RLPFC (Morita et al., 2008). Furthermore, it has been proposed that the PFC more generally and the frontoparietal control network represent key neural architecture that is essential for the formation and maintenance of the concept of self (de Caso et al., 2017; Vogeley et al., 1999). It is possible that such associations may, at least in part, underlie the finding observed in the present study with regard to this construct, which appears to show an opposite trend to the trait domain that it constitutes (i.e., N). The associations between RS-related hemodynamic response and all other facets of N were consistent with the pattern of associations observed with N.

The association between N and the GS-related activation change within the LLPFC was similar to what was observed in the context of RS and RLPFC, where lower N was linked to a stronger hemodynamic response associated with GS within the LLPFC (while higher N was not associated with a significant change in activation). Unlike in the case of RS, both interpersonally relevant facets of N (Angry Hostility [N2] and Self-Consciousness [N3]) demonstrated similar trends to that of N with regard to GS-related activation change. All other facets of N also demonstrated patterns of associations with GS-related hemodynamic response that are consistent with N. This further suggests the possibility that N is an interpersonal disposition that confers a lower cognitive control-related neural response in specific regions of the PFC, both with regard to the overall trait domain and across most of its constituting facets, with the possible exception of self-consciousness.

Extraversion

In contrast to N, higher E was associated with a stronger RS-related hemodynamic response within the RLPFC, compared with lower E. This finding is consistent with previous research that demonstrates a positive association between RS-related behavioral tasks and lateral PFC activation (Eisenberger et al., 2005; Rodrigo et al., 2016). It has been suggested that the link between higher E and greater lateral PFC activation during RS may reflect a higher propensity for extroverts to engage in task-relevant cognitive control (Eisenberger et al., 2005). The present results appear to further contribute to this idea but also suggest important variability across its constituent facets with regard to their associations with RS-related neural activation. Specifically, while two inherently interpersonal facets of E (Gregariousness [E2] and Assertiveness [E3]) demonstrated patterns of associations that were similar to E, a third (Warmth [E1]) did not demonstrate a significant relationship with the RS-related hemodynamic response in the RLPFC.

The association between E and the GS-related hemodynamic response within the LLPFC was similar to the one seen during RS. Specifically, higher E was linked to a higher increase in oxy-Hb when engaging in GS compared with lower E. Similar to RS, both Gregariousness (E2) and Assertiveness (E3) demonstrated similar trends to E, whereas Warmth (E1) did not demonstrate a relationship with the GS-related hemodynamic response. Previous neuroimaging research examining Warmth and Altruism (a facet of A) have linked these interpersonal processes to empathy-related neural activity within temporoparietal and medial prefrontal regions of the brain (Haas et al., 2015). These results may suggest that Warmth, unlike Altruism which demonstrated associations with cognitive control-related processes in the present study, may represent an aspect of empathy that is independent of cognitive control-related processes.

Variability was also seen with regard to other facets of E, where Excitement-Seeking (E5) showed a pattern of associations that were similar to E during RS, but Activity (E4) demonstrated an opposite trend. Positive Emotions (E6), on the other hand, was not associated with the RS-related hemodynamic response within the LLPFC. During GS, the pattern of associations between Activity (E4) and oxy-Hb change during GS was similar to that of E, while both Excitement-Seeking (E5) and Positive Emotions (E6) did not demonstrate a significant relationship to the hemodynamic response. Although E4, E5, and E6 are not considered inherently interpersonal facets (Table 1), these results highlight the possibly nuanced nature of cognitive control-related processes that may underlie the broader trait domain of E.

Agreeableness

Contrary to expectations, higher A was associated with a lower RS-related hemodynamic response relative to lower A. This finding appears to contradict a previous study that demonstrated an opposite result. Specifically, higher levels of A, as measured by the Big Five Inventory (BFI; John & Srivastava, 1999), were linked to a stronger hemodynamic response within the RLPFC during an identical RS-related paradigm (Rodrigo et al., 2016). This discrepancy, at least in part, may be accounted for by differences in how the construct of A is captured across various instruments (Miller et al., 2011). Specifically, it has been suggested that A, as conceptualized within the NEO-PI-R, represents elements of Modesty (A5) and Straightforwardness (A2), which are suggested to be not fully captured within the BFI conceptualization of A. Perhaps consistent with this notion is the qualitative observation that higher Straightforwardness (A2) in the present study was associated with the lowest observed hemodynamic response within the RLPFC. Additionally, however, a previous investigation of 20 healthy adults also revealed a positive correlation between the hemodynamic response within the RLPFC linked to a specific aspect of RS (i.e., detection of response discrepancy) and A as measured using the Japanese version of the NEO Five Factor Inventory (Ikeda et al., 2014). This perhaps suggests that the RS-related hemodynamic response might be further nuanced based on specific subprocesses that constitute RS.

Despite a high degree of positive correlation between A and its facets, Trust (A1) demonstrated a trend that was opposite to the broader trait domain and all other facets of A with regard to its associations with the RS-related hemodynamic response. Specifically, these results suggest that individuals who report a higher propensity to perceive others as trustworthy also demonstrate a stronger hemodynamic response within the RLPFC during RS. Previous research has suggested that, just like in the case of A (Koelsch et al., 2013), RLPFC is a key neural region that subserves interpersonal trust (Filkowski et al., 2016). The present results may further this knowledge by suggesting that the association between this neural substrate and Trust is perhaps nuanced, as it appears to be unique from its general trait domain of A during RS-related processes.

Further highlighting the nuanced nature in which A might relate to cognitive control-related processes, the association between A and the GS-related hemodynamic response within the LLPFC was opposite to that observed in relation to RS. Specifically, higher A was linked to relatively higher activation within the LLPFC compared with lower A. Therefore, unlike in the cases of N and E, which demonstrated similar patterns of associations across both RS- and GS-related hemodynamic responses, A appears to demonstrate a pattern of neural recruitment that might be differentiated across specific subconstructs of cognitive control. Additionally, while five of the six facets of A (including Trust [A1]) demonstrated patterns of association with GS-related activation change that were similar to the overall trait domain, Tender-Mindedness (A6) demonstrated an opposite result, with individuals who reported lower Tender-Mindedness demonstrating a higher GS-related hemodynamic response within the LLPFC.

Conscientiousness and Openness

Consistent with previous research (Rodrigo et al., 2016), higher levels of C were linked to a stronger hemodynamic response within the RLPFC, as compared to lower C. This pattern of association was also seen with regard to the GS-related neural response within the LLPFC. Divergences were seen, however, with regard to the associations between the facets of C and the neural responses associated with RS and GS. Of note was the unexpected finding of higher Deliberation being linked to a larger hemodynamic response within the LLPFC, which appears to be contradictory to previous research that has demonstrated an opposite trend but within a smaller group of participants that does not overlap with the sample described in the present study (Ruocco et al., 2014). Taken together, these findings may suggest that, unlike N, C may represent the propensity to adequately engage neural systems that underlie different aspects of cognitive control, albeit with some nuances at the level of its facets.

While a previous study that examined O using a briefer measure of the FFM found no association between this trait and RS-related hemodynamic activity (Rodrigo et al., 2016), the present study indicates that higher O may be associated with a larger hemodynamic response during RS, compared with lower O. This pattern of associations was also consistent at the level of its constituent facets. While the trait domain O was not associated with the GS-related hemodynamic response, many of its facets demonstrated significant relationships with GS-related neural activity within the LLPFC, the directions of which appeared to vary across some facets. This highlights the possible differences that may exist with regard to how cognitive control-related processes may underlie this aspect of personality that may influence interpersonal functioning depending on the context.

Limitations and future directions

The present study examined a thin slice of cognitive control, which represents an incredibly complex cognitive process. Specifically, we focused on two previously established neural correlates of cognitive control subconstructs (i.e., RS and GS) in specific regions of the PFC. As previously mentioned, it is important to recognize that cognitive control requires the interplay between several neuroanatomical networks spanning cortical and subcortical regions, and although lateral PFC regions examined in the present study are necessary, they are not sufficient for the successful exertion of cognitive control. On the other hand, to date, little guidance exists with regard to how cognitive control processes may be associated with interpersonally relevant dispositions. To that end, the present study provides important early evidence that may guide future research, which should examine how the involvement of cognitive control processes in interpersonal functioning can be further delineated with better neuroanatomical specificity. Accordingly, future research could contextualize associations between cognitive control and interpersonal functioning within the structural and functional nuances that might better differentiate between subconstructs of cognitive control.

Despite its many advantages, fNIRS also presents several limitations as compared to other neuroimaging modalities, such as fMRI. Of note is its limited penetration into cortical tissue, only allowing the surface of the cortex to be examined. Promisingly, however, previous fNIRS findings highlighting lateral PFC involvement in cognitive control have been largely consistent with fMRI findings that examine similar constructs (Rodrigo et al., 2014; Ruocco et al., 2014). fNIRS also does not provide a measure of cortical volume and is solely focused on relative change in hemodynamic activity. In this vein, it is important to consider that previous structural neuroimaging findings suggest that personality traits may be linked to individual differences in cortical volume (DeYoung et al., 2010). Therefore, future research should attempt to account for the role of structural, in addition to functional, aspects of cognitive control processes in interpersonal functioning.

Additionally, the present study focused on examining nuances in the neural signature that were associated with successful cognitive control (i.e., when all participants demonstrate mostly accurate behavioral performances). This allowed the assessment of RS and GS, with minimal overlap with neural processes that may subserve error correction, which constitutes performance monitoring (another key aspect of cognitive control). Future research could extend these findings by also examining how this additional aspect of cognitive control may relate to interpersonal traits and facets. We also did not obtain repeated measurements, which would have allowed us to quantify the reliability of the fNIRS signal as it pertains to the cognitive tasks included in the study. Additional research is needed to determine whether the hemodynamic response is reliably activated by the RS and GS tasks and the potential impacts on the observed associations with interpersonal dispositions. Furthermore, the present study demonstrates the presence of important distinctions in associations between the propensity for interpersonal behaviour (i.e., interpersonal traits and facets) and the neural signature linked to aspects of cognitive control, even when such patterns of associations may not be apparent at the behavioral level. Therefore, it would be important for future research to extend these findings and explore how these possible distinctions in the neural correlates of cognitive control may translate into interpersonal behavior. Finally, research is needed to clarify, where possible, the directionality and mechanisms underlying the observed findings.

Conclusions

To our knowledge, the present study is the first to explore the associations between two key cognitive control-related processes and personality traits and facets within the FFM, providing initial evidence to suggest that important divergences may exist at the neural level in terms of how these aspects of cognitive control may underlie interpersonal dispositions. These results underscore the importance of distinct cognitive control-related processes that may underlie dispositions that describe an individual's propensity to engage in various types of interpersonal behavior. While some inherently interpersonal trait domains appear to be related to lower hemodynamic responses and others to stronger responses within key prefrontal neural regions across the two aspects of cognitive control examined, these patterns of associations were not always consistent with their constituent facets. Specifically, important nuances were observed across facets that constitute trait domains, with some facets demonstrating trends that were opposite to their traits. Overall, the present study provides a preliminary roadmap for future research designed to better understand how nuances in cognitive control that underlie the many traits and facets that guide how individuals may navigate their interpersonal milieu.

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Declarations

Dr. Hasan Ayaz was involved in the development of the optical brain imaging instrumentation utilized in the present study and was offered a minor share in fNIR Devices, LLC.

Conflicts of interest All other authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Open Practices Statement None of the data for the experiments reported here are available in a public repository. Data and programming scripts (e.g., tasks, statistical analyses) are available on reasonable request from the corresponding author. None of the experiments were preregistered.