FROM GENERAL FACTORS TO RESPONSE GENERALISATION: THE IMPORTANCE OF THE CEREBELLUM FOR MENTAL HEALTH AND SOCIAL EFFECTIVENESS

Nicholas D. Walsh

School of Psychology, University of East Anglia

Nicholas Walsh: Nicholas.walsh@uea.ac.uk

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Abstract

Various psychometric general factor models exist to describe a diverse range of human psychological traits e.g. general factors of intelligence, personality and psychopathology. Historically, these latent traits have been viewed and studied as distinct constructs. However, accumulating evidence demonstrates empirical overlap, and conceptual proposals have been made arguing that collectively these traits form a marker of general social effectiveness. Here I argue that the cerebellum has an important, and previously neglected role in supporting diverse general factor psychological traits that enable such social effectiveness. In this conceptual article, I review evidence derived largely from neuroimaging studies, that these general traits (intelligence, personality, psychopathology and others) share overlapping neural correlates, and potentially shared underlying computations in the cerebellum. This is important as the cerebellum has an integrative role in skilled behaviour and psychological flexibility by enabling cognitive, affective and behavioural generalisation and adaptation across diverse environmental contexts. This article also discusses the importance of the cerebellum for understanding general factor development, given the early maturational timing of the cerebellum, and high sensitivity to early environmental influence. Finally, I propose a cerebellar role within the Hierarchical Taxonomy of Psychopathology (HiToP); an important framework for understanding of the latent transdiagnostic structure of psychopathology. If correct, consideration of the cerebellum can facilitate integration of psychometric and translational neuroscience perspectives to provide a broader and unified biopsychosocial understanding of psychological, and specifically mental health phenomena.

Keywords: Cerebellum, Intelligence, Personality, Psychopathology, Development, HiToP

The field of psychology has created a vast number of constructs to describe putative psychological phenomena. For example, heterogeneous labels can be used to describe constructs such as 'control' (Skinner, 1996) and 'goals' (Austin & Vancouver, 1996). Psychological constructs usually describe psychological phenomena as a *structure*, *process* or *representation*. For example memory can refer to both memory structures, processes and representations. Examples of such psychological constructs used in the individual differences literature include strengths, interests, traits, capabilities, abilities, resources, skills, intelligence, personality, competencies. However, it is unclear whether the above constructs are isomorphic, overlapping or distinct psychological phenomena. Various general factors have been proposed using psychometric methods to model this diverse range of human psychological constructs. The most investigated general factors being those of intelligence, personality and more recently, psychopathology. The aim of this integrative review will be to discuss such general factors and hypothesise that together they form a marker of general social effectiveness. In addition, this review will discuss how these general psychological factors have a shared neuroanatomical basis involving the cerebellum. If correct, this hypothesis will can facilitate integration of psychometric and translational neuroscience perspectives to provide a broader and unified biopsychosocial understanding of human psychological functioning.

Thus this review will be organised into three parts. The first part will discuss general factors in psychology; how they are derived; the domains they are reported in; evidence of overlap between general factors; and whether there is evidence for a more general construct such as social effectiveness underlying all general factors. The second part will highlight the evidence for a cerebellar involvement underlying these psychological constructs. It will then discuss why the cerebellum may be implicated in these general factors, in terms of what is known about its functions, structure and anatomical connectivity. The final part will synthesise the evidence implicating the cerebellum in relation to social effectiveness and

also discuss limitations, or lack of evidence for the hypothesis that the cerebellum underlies these psychological constructs.

A detailed review of all available evidence for general psychological factors and supporting cerebellar literature is beyond the scope of this article. Rather, this review is intended to serve as an integrative tour of the conceptual landscape and lay the foundations for future research to comprehensively investigate the hypothesis I present.

Part 1: General factors in psychology

What general factors have been derived?

The most investigated general factor construct is that of general intelligence. More recently, additional general factors of personality, psychopathology, development, and executive functioning have received attention in the literature. It is also unclear whether, and if so how, the constructs relate to other psychological constructs such as creativity and other constructs underlying human functioning such as health, performance and fitness.

Psychological constructs such as intelligence, personality and psychopathology are not directly observable or measureable phenomena. Rather these constructs are described as 'latent' constructs or variables (Bollen, 2002; Brunner, Nagy, & Wilhelm, 2012) because they emerge only through measurement on assessments designed to tap into these constructs. Such assessments could include behavioural tasks of certain abilities or subjective experiences assessed via self-report questionnaires.

The most researched general factor of psychology is intelligence (Deary, 2012). Intelligence is a broad umbrella term, conceptually similar to cognitive abilities with no accepted definition, although consensus statements have been proposed (Neisser et al., 1996).

However, since Spearman (1904), it is accepted that if a group of individuals are given a number of assessments of cognitive abilities, then there will be a positive correlation (positive manifold) between test scores. From this a latent variable can be proposed, in the case of intelligence, termed 'g', to account for a significant proportion (usually about 40-50%) of the between-individual variation on test performance (Plomin, DeFries, Knopik, & Neiderhiser, 2016).

There have been conceptual developments to the structure of intelligence since Spearman. Currently the most widely accepted model is the Cattell-Horn-Carroll model that proposes a hierarchical, three-stratum model consisting of: stratum I, "narrow" abilities; stratum II, "broad abilities"; and stratum III, consisting of a single "general ability" (or g) (Flanagan & Dixon, 2014). This finding appears to be a culturally universal phenomenon (Warne & Burningham, 2019) and not limited only to humans (Reader, Hager, & Laland, 2011). The general intelligence construct also appears to have predictive validity and is the most important predictor for important life outcomes such as educational attainment, job performance, and health (L. S. Gottfredson, 1997; Linda S. Gottfredson & Deary, 2016).

A general factor of personality, known as the GFP, has also been reported. This was derived initially from the five-factor model of personality (J. Musek, 2007; Janek Musek, 2017), but is also present in other personality and temperament measures (J. P. Rushton & Irwing, 2009, 2011; Veselka et al., 2012). The five factor model comprises five-dimensions of Emotional stability/Neuroticism, Extraversion, Openness, Agreeableness and Conscientiousness). Digman (1997) was the first to show that, rather than comprising independent dimensional traits of personality, two factors or metatraits, labelled *Alpha* (Emotional Stability, Agreeableness, Conscientiousness) and *Beta* (Extraversion and Openness) were evident in data derived from 14 studies. Such metatraits were also found by others such as DeYoung et al. (2006; 2002) who gave the two dimensions the labels *Stability* and *Plasticity*.

However, a further higher-order personality dimension known as the Big One can also be derived through factor analytic modelling (J. Musek, 2007; J. Philippe Rushton & Irwing, 2008). Thus again, a hierarchical model has been proposed with a general factor at its apex. Hofstee (2001) introduced a general “p-factor” (personality factor), analogous to ‘g’ for mental ability, but this never caught on in the literature, and it was not until Musek’s (2007) paper did the idea of a GFP take hold. Hofstee (2003) went so far as to label ‘p’, “the Primordial One” (p. 249). The GFP has been proposed to correspond to the lay notion of personality of “a good person”, someone who is altruistic, agreeable, relaxed, conscientious, sociable, and open with high levels of well-being and self-esteem. The general factor of personality finding has been replicated (Janek Musek, 2017), and as with ‘g’ has demonstrated cross-cultural stability (Aghababaei, 2013; J. P. Rushton et al., 2009). It has been found relate to other psychological constructs such as affect, well-being and self-esteem (Janek Musek, 2017).

In the psychopathology domain another general factor, known as the p-factor, has also been reported. It is noted in the psychopathology literature that Lahey et al. (2012) were the first to identify a general factor of psychopathology who applied confirmatory factor analysis to a nationally-representative longitudinal cohort study; however, Rushton and Irwing (2011) had previously derived a general factor derived from clinical samples. Caspi et al (2014) independently derived a general psychopathology factor, that they termed the “p-factor” (this time ‘p’ for psychopathology), from the Dunedin longitudinal cohort. Caspi et al (2014) proposed a hierarchical model consisting of a general psychopathology factor and specific Externalising, Internalising and Thought Disorder factors. This finding of a general factor of psychopathology derived from psychopathological measures used in child and adult samples has been repeatedly independently replicated in groups around the world, though there is considerable debate as to its meaning and role in psychopathology (Caspi & Moffitt, 2018).

Building on this work, a Hierarchical Taxonomy of Psychopathology has been proposed to organise psychopathology phenomena. This taxonomy can be understood at varying levels of abstraction, moving up from 1) signs, symptoms components to 2) syndromes/disorders to 3) subfactors to 4) spectra and the general psychopathology factor at the superspectrum apex (C. C. Conway et al., 2019; Kotov et al., 2017).

However, the presence of general factors in psychology is not limited to only intelligence, personality and psychopathology constructs. There is also evidence for a general factor of executive functioning. Again, this comprises a hierarchical structure with a common executive functioning factor above specific updating, shifting and inhibition abilities (Miyake & Friedman, 2012; Miyake et al., 2000; Smith, Banich, & Friedman, 2019; Wiebe, Espy, & Charak, 2008). A general factor of development has been derived both in terms of child and adult development. Rhemtulla and Tucker-Drob (2011) found a general development factor could account for 42% of individual differences in longitudinal change on linguistic, mathematics, reading, gross motor, and fine motor skill assessments. There has also been investigation of a general factor of development in older samples. Tucker-Drob et al. in a recent meta-analysis of published studies on this question found clear evidence for a general factor of cognitive aging that strengthens with advancing adult age (Tucker-Drob, Brandmaier, & Lindenberger, 2019). In a large sample of older adults (n=1009) taken from Vietnam Era Twin Study of Aging (VETSA), Kremen et al. (2019) examined the effect of later life education and cognitive-intellectual activities after controlling for earlier general cognitive ability. It was found that subsequent education and cognitive-intellectual activities accounted for less than 1% of the variance in midlife cognitive functioning. This indicates that this general cognitive factor is fully-formed by late adolescence and early adulthood.

Other, less researched general factors reported in the psychology and related literatures include a general factor of human performance (Furnham, von Stumm, Makendrayogam, & Chamorro-Premuzic, 2009), job performance (Viswesvaran, Schmidt, & Ones, 2005),

academic achievement (Marsh, Byrne, & Shavelson, 1988), psychomotor functions (Carretta & Ree, 1997), motor competence (Utesch et al., 2016), physical fitness (Utesch, Dreiskamper, Strauss, & Naul, 2018), and numerous other constructs (Ree, Carretta, & Teachout, 2015).

The general factor of personality and social effectiveness

Returning to the GFP construct, much has been written on the relation between the GFP and other social constructs such as social desirability and social effectiveness. An important question is whether social desirability is a nuisance factor in personality testing, or part of personality itself reflecting self-deception or impression management?

Backstrom et al. (2007) examined higher-order personality factors in from a data-set of Five Factor personality items. A personality model containing one higher-order factor and five-personality factors beneath showed best model fit. In a subsample of 196 subjects for which there was also data on a social desirability test, the single higher-order factor was shown to be positively associated with social desirability. Backstrom et al. (2009) further examined the association of the GFP with social desirability. They created a new personality inventory by rephrasing items in order to minimise the extent to which they are seen as social desirable. Using a sample of 620 participants recruited via the internet, they found that rephrasing the items made them substantially less socially desirable.

Rushton and Erdle (2010) conducted two studies investigating whether socially desirable responding accounts for the GFP. They found that the GFP remained intact after controlling for socially desirable responding using the Lie Scale from the Eysenck Personality Questionnaire. They concluded that a social desirability response set does not explain the GFP. Erdle and Rushton (2011) conducted four studies again examining whether social desirability or self-esteem account for the GFP. In all four studies, controlling for these

constructs made very little difference to the mean loadings on the GFP. Thus they conclude that the GFP is substantive, rather than an artefact of evaluative bias.

Another proposal is that the GFP reflects something more fundamental than a social desirability response bias, and in fact reflects social-effectiveness (Dimitri van der Linden, Dunkel, & Petrides, 2016). Social-effectiveness is an evolved trait associated with positive social outcomes that had relatively strong adaptive advantages during human development. Highly socially effective individuals are those that “have the knowledge, skills, and motivation to act in ways that others consider socially desirable, which subsequently increases their chances of achieving social goals. Consequently, high-GFP individuals may have a higher probability of being selected as mate, co-worker, or leader”.

Dunkel and Van der Linden (2014) tested the ‘social effectiveness’ hypothesis directly by examining the relation between the GFP, socially-desirable responding and social effectiveness. 286 undergraduates from a previously collected dataset that comprised a number of personality inventories. Social-desirability was assessed with the Marlow-Crowne inventory as well as scales from the other personality inventories. Three measures of social-effectiveness were collected that reflected a participants’ rating of their own social-effectiveness in broad general terms. That is, the referred to social-effectiveness was not within a specified relationship or circumstance. The GFP and measures of social-effectiveness were significantly correlated even after controlling for social-desirable responding. The authors acknowledge the potential shortfalls from this archive dataset such as it being a convenience sample with a small sample size. However the authors conclude that this provides support for the notion that a key aspect of the GFP is social effectiveness.

Van der Linden et al. (2014) examined the relation of the GFP to performance on video-based situation tests measuring social knowledge and skills. In two studies it was found that that high-GFP individuals were better able to indicate the appropriate social behaviour in a

situational judgment test and were rated higher by others on leadership skills. High-GFP was also associated with actual display of social behaviour in a situational webcam test and greater reported leadership experience in organizations. Thus there exists objective evidence to support the subjective evidence found previously.

Polek et al. (2018) used data from a large community sample of adolescents and young adults ($n=2443$) to examine the relation between personality, psychopathology traits, mental health assessments and service use. They found a general factor and four specific factors emerged. The authors propose that this general factor corresponds to a single latent trait indexing impairment in social functioning. Thus there are links between the p-factor and social effectiveness constructs. This is echoed by a recent review article integrating 31 meta-analyses across 30 different clinical populations that proposes that social cognitive dysfunction is a transdiagnostic clinical marker of psychopathology (Cotter et al., 2018).

Dunkel et al. (2019) examined whether it was possible to identify early developmental markers of the GFP, given that the GFP is partly heritable. To do this, the authors examined firstly whether the GFP can be predicted by childhood temperament, as assessed by sociability towards strangers from ages 1-4. A positive association was found ($r=.518$) demonstrated that greater social responsiveness predicted the GFP at age 12.

There is therefore evidence that the GFP may reflect a degree of both social desirability and social effectiveness, though the social effectiveness does account for a larger share of the variance.

Criticisms of general factor modelling

Agreement on the presence of general factors in psychology is not universal. There is a long history of critiquing general factors modelling in the domains of intelligence (Thomson, 1916;

van der Maas et al., 2006), personality (Revelle & Wilt, 2013) and psychopathology (van Bork, Epskamp, Rhemtulla, Borsboom, & van der Maas, 2017) and space precludes a full discussion of the debate *minutia*. There is also debate as to the meaning of such general factors and whether they are simply statistical phenomenon or are in fact psychologically meaningful and play a causal role in human behaviour. An excellent discussion of these issues as applied to the p-factor is a review by Caspi and Moffitt (2018). Due to the complexity of these issues, I will simply acknowledge them here and discuss further later in the article.

Are these general factors related?

In addition to the work discussed above that has established the presence of general factors in psychology, work has also been conducted to establish whether the above general factor constructs are isomorphic, overlapping or distinct psychological phenomena. This next section will highlight some of the progress that has been made in understanding possible relations between general psychological factors. This literature is vast and therefore this review will selectively focus on studies that have compared general factors with other general factors.

Personality and intelligence

Much work has been conducted to understand the relation of general intelligence and general abilities (from now on referred to as 'g') with other general factors. Many authors have discussed whether intelligence and personality are in fact similar constructs (Ackerman, 2018). Wallace provided an abilities conception for personality (J. Wallace, 1966) and DeYoung has argued that intelligence should be considered as subcomponent of personality (C.G. DeYoung, 2011). However, this section will consider studies specifically examining relations between g and the GFP.

Shermer and Vernon (2010) examined the relation between g and the GFP in 507 siblings. The siblings were split into two groups. A significant correlation of .256 was found in the first sample and .279 in the second sample. Given the discussion in the literature about the relation between the GFP and social desirability (see more below), the authors also examined the relation of g and the GFP to social desirability. The GFP significantly correlated with social desirability but g did not, suggesting the GFP represents something more than social desirability alone.

Using data from the Vietnam Experience study containing 4462 Vietnam War veterans, Irwing et al. (2012) examined the relation between MMPI score and g . A significant negative correlation was found (because the MMPI assesses psychopathology) of -.23 between GFP (Abnormal) and g . The authors conclude that the reason for this low (yet significant correlation) is that both intelligence and personality are to a degree mutually exclusive evolutionary survival strategies, the first aimed at generating resources and the second at maximizing one's share of resources.

Dunkel (2013) used Q-sort data from a longitudinal child development study to examine the relation between the other-rated GFP and g . There were significant associations between the GFP and g scores across the study waves with the correlation between average g and GFP (across ages) being .46. Dunkel et al. (2014), this time using data from a longitudinal study of high school students collected in the 1960s. The Student Activities Inventory (SAI) was used to assess personality and sixteen tests of cognitive ability were used to assess g . Exploratory factor analysis was used to generate the GFP and g from the data sets. Again, a significant positive correlation was found between g and the GFP ($r=.25$).

In addition to standard individual level analyses; large-scale studies have examined national-level estimates of personality and intelligence (Lynn & Meisenberg, 2010; McCrae &

Terracciano, 2005). Dunkel et al (2014) examined the relation between national-level intelligence and personality estimates. A significant correlation was reported (.44) and that this was not a function of acquiescent reporting.

In another study by Dunkel et al. (2014) using a prison sample of 2837 male offenders in an effort to control for social desirable responses. Using the California Personality Inventory (CPI) and Minnesota Multiphasic Personality Inventory (MMPI) to assess the GFP and the California Achievement Test Battery (CATB), General Test Battery (GTB) to assess g. significant correlations were found between the g and the GFP tests with the largest correlation being with the CATB and CPI (.35).

Loehlin et al. (2015) examined for the presence of a genetic correlation between g and the GFP using data from US, UK, Croatian, Dutch and Australian twin samples. Various tests of personality and intelligence were used across the samples. However, no genetic correlation was found across the samples. The authors discuss various interpretations of the data such as 1) general factors exist but are uncorrelated genetically 2) previous findings are due to measurement biases 3) personality and intelligence should not be considered at the general factor level, or that something has changed over time since the samples were collected and this has affected some important underlying process.

In a replication of their earlier (2013) study, Dunkel and Cabeza de Baca (2016) assessed in 185 the relation between personality, assessed using the California Child Q-set, and g assessed via verbal and non-verbal intelligence tests. In this study the correlation between g and the GFP was $r = .3$.

A further study by Kretzschmar et al. (2018) combined several data sets to assess the association between the GFP, derived via five-factor measures and g, assessed via the Berlin Intelligence Structure test. This study found a correlation of 0.15.

Shermer and Goffin (2018) assessed GFP and g relations using a sample of 1198 job candidates. The GFP was derived from the Personality Research Form and Sixteen Personality Factors measures and Intelligence was assessed via the Employee Aptitude Survey. No significant association between the GFP and g was found in this study.

In summary, studies have demonstrated significant associations between 'g' and the GFP. However, exceptions exist. In addition, these correlations, although significant are not high and (on average) are of .3 magnitude. There may be methodological factors such as assessment method that account for between-study variations. Or it may be that such correlations are reflect the small degree of psychometric overlap between these constructs.

Intelligence and development

Evidence also links the general factors of intelligence and development. Baughman et al. (2016) examined whether individual differences in intelligence and development reflected common mechanisms. The study involved comparing cognitive profiles of groups of younger and older children matched on overall mental age (MA) using standard tests of intelligence (British Abilities Scales-II; BAS-II, and Wechsler Intelligence Scale for Children, 3rd edition; WISC-III). In both experiments, MANOVAs revealed few differences in the profiles of younger and older MA-matched children. It was concluded that the degree of similarity between cognitive profiles of younger and older MA-matched groups suggests a common mechanism underlies variability in individual differences and development.

Cognitive abilities and executive functioning

Links have also been proposed between the general constructs of cognitive abilities (g) and executive functioning. Ackerman et al. (2005) in a meta-analysis comparing working memory

(a subset of executive functioning hierarchical models) and g found a correlation substantially less than unity implying they are overlapping but not identical constructs. The same conclusion was also stated by in a later review by Conway et al. (2003). However, there are few studies directly comparing general factors of executive functioning and intelligence. One study that directly compared general factors of intelligence and executive functioning did find evidence of a significant association (Brydges, Reid, Fox, & Anderson, 2012). In their study, Brydges et al. (2012) assessed executive functioning and intelligence in a sample of 215 typically developing children aged between 7 and 10 years of age. A range of executive and intelligence tasks were used and factor analysis and structural equation modelling was used to derive general factors for both constructs. A correlation of .89 was found between executive functioning and fluid intelligence with the authors concluding a high degree of overlap between the two general factors.

In another developmental study, Wu et al. (2017) how motor and general cognitive abilities related to later executive functions. 96 infants were assessed at ages 1, 2 and 3. At ages 1 and 2 tasks of motor ability and g were assessed and at age 3 executive functions were assessed. Although no general factors of EF were extracted in the data, performance on the earlier assessments were highly predictive of later EF performance.

Emotional intelligence, general intelligence and personality

The construct of emotional intelligence (EI) has also been proposed as a construct distinct from both general intelligence and personality (Mayer, DiPaolo, & Salovey, 1990). An early factor analytic study by Schutte et al. (1998) identified a general factor of EI corresponding to the general factor described in the Salovey and Meyer theory. A number of studies have examined the statistical relation between other general factors such as g and personality. Schulte et al. (2004) examined the relation between EI, g and personality (although not deriving a GFP as this was not yet a recognised construct). A significant correlation was

found between the Mayer-Salovey-Caruso Emotional Intelligence Test (MSCEIT) and g assessed with the Wonderlic Personnel Test ($r=0.454$).

With regards to the relation of EI and the GFP, this has been examined in a number of studies (Dimitri Van der Linden, Tsaousis, & Petrides, 2012; Veselka et al., 2009). Perez-Gonzalez and Sanchez-Ruiz (2014) found that the association between EI and the GFP was higher than the relation between EI and lower-level Big Five factors (Big Two and Big Five). In a meta-analysis of published literature on this question, van der Linden et al. (2017) reported a correlation of 0.86 between trait EI and the GFP, suggesting the two constructs are virtually synonymous. The association between ability measures and GFP, although significant was lower ($r=0.28$) thus demonstrating the importance of whether EI is construed as an ability or trait.

Personality and psychopathology

Associations have also been examined between the general factor of psychopathology and other general factor constructs. As mentioned earlier, a summary of this work based on the GFP and clinical personality measures (e.g. MMPI) can be found in Rushton and Irwing (2011). More recently, Oltmanns et al. (2018) specifically investigated the relations between the p-factor, the GFP and a general factor of personality disorder (GPD). In two studies using self-report (study 1) and multimethod data (study 2), significant associations were found. The correlation between the GFP and p was .70, the correlation between the GFP and GPD was .90 and the correlation between GPD and p was .92. Thus there is clearly high overlap between these constructs. The authors conclude that what all of these general factors might have in common, or perhaps how they should be understood, is that they simply reflect extent of impairment or dysfunction within the respective persons' lives. This would occur irrespective of the basis for that dysfunction or impairment, whether it be from the presence of a mood disorder, a psychosis, a PD, or a personality trait. Finally,

Rosenstrom et al. (2019) have also found evidence for a general factor underlying both normative and clinical personality measures.

Executive functioning and psychopathology

There is also evidence for an association between the p-factor, g and executive functioning. In a large sample of 2,144 community-based adolescents, Castellanos-Ryan et al. (2016) found the p-factor to be associated with lower performance IQ. Another large-scale study involving another large sample of 8012 Brazilian children (Martel et al., 2017) found that a p-factor derived through parent interviews of child psychopathology was significantly associated with a global executive factor derived from a battery of inhibitory control, working memory and time processing tasks. This association between global EF and the p-factor has also been replicated in adults (Bloemen et al., 2018) using a longitudinal Tracking Adolescents' Individual Lives Survey (TRAILS, n=2230). However, other studies have also found associations between general EF and specific symptom clusters (Bloemen et al., 2018).

Intelligence and Creativity

It is worth noting that associations between constructs like intelligence, personality, executive functioning have been theorised to also be associated with other psychological constructs such as creativity and emotion regulation. Creativity is an important construct that links with later discussed findings regarding the association of the cerebellum with general psychological factors. Silvia (2015) reviewed the literature applying latent variable modelling to creativity investigations and concluded the constructs are more similar than have previously been thought. Benedek et al. (2014) reported a correlation of .34 between g and their measure of creativity assessed through the divergent thinking task. Feist (2019) discussed creativity in light of its association with the Big Two model of personality. It would

also be of interest to examine if there is an association of creativity with the Big One GFP factor, but no studies to date have investigated this question.

Summary of part 1

This section has reviewed the literature on the different general factors proposed in the psychology literature. There is compelling evidence to support the existence of a wide range of general factors and also evidence demonstrating varying degrees of overlap between them, both when studied cross-sectionally and longitudinally. There is also evidence linking these general factors to other, less well-defined psychological constructs such as creativity. Finally, there is also a suggestion that that certain psychological constructs can be linked under the broader evolved trait construct of 'social effectiveness'.

Part 2 – The cerebellum and general factors

In this next section I will present the evidence implicating the cerebellum in general psychological factors. This will discuss cerebellar findings reported in neuroimaging studies of intelligence, personality, psychopathology, emotional intelligence, creativity, and social processing. It will also discuss the role of the cerebellum in broader aspects of human functioning by discussing cerebellar findings in relation to health and fitness, as this is a key factor related to social effectiveness and adaptive behaviour. There are compelling reasons why the cerebellum should significantly contribute to general psychological factors. The cerebellum contains four times as many neurons as the cortex (Lent, Azevedo, Andrade-Moraes, & Pinto, 2012), and has a very high ratio of afferent to efferent pathways (40:1) (Morales & Tomsick, 2015), implying a significant integrative role in psychological processing i.e. much more information comes into the cerebellum than goes out. Recently, it has been found that Cerebellar BOLD signals temporally lag the cortex by hundreds of milliseconds

(Marek et al., 2018), again supporting proposal that the cerebellum has a modulatory role of psychological processing (Schmahmann, 1991).

The cerebellum and intelligence

Associations have been reported between cerebellar structure and function and tests of general intelligence. It is a long held view that the cerebellum contributes to motor skills and flexibility (Glickstein, Strata, & Voogd, 2009). In an influential review, Leiner et al. argued for a cerebellar role in mental skills beyond that of the classic role in motor functioning (Leiner, Leiner, & Dow, 1986). Theoretical review papers have also linked the cerebellum with general intelligence (B. Anderson, 1995; Schmahmann, 1991). This section will review functional and structural neuroimaging studies of intelligence that have reported associations in the cerebellum.

Functional imaging studies

In a very early study, Haier et al. (1992) using Positron Emission Tomography (PET) found significant associations between cerebellar metabolism and intelligence whilst performing the game “Tetris”. In a functional MRI study, by Gray et al. (2003) assessed how gF (assessed via the Raven’s Advanced Progressive Matrices) related to brain activity whilst participants completed the n-back task. The task contained both lure and non-lure trials designed to increase attentional control demands. On lure trials, gF correlated positively with lateral cerebellar activity. Pezoulas et al. (2017) conducted a resting state imaging study investigating correlations between cerebellar activity and functionally connected regions. 136 healthy subjects taken from the Human Connectome Project (HCP) database were separated into two groups composed of 69 low-IQ and 67 high-IQ subjects. Differences in network connectivity properties were found for the two groups and interpreted as higher-IQ

individuals demonstrating higher neural efficiency in the cerebellum compared to low-IQ individuals.

An association has also been reported between the concept of 'cognitive reserve' and task performance across a battery of cognitive tests (Stern, Gazes, Razlighi, Steffener, & Habeck, 2018). Cognitive reserve has been proposed to explain individual differences in susceptibility to cognitive or functional impairment in the presence of age- or-disease related brain changes (Stern, 2012). Stern et al. (2018) had 255 individuals, aged 20-80 perform a battery of 12 cognitive tasks. Across this battery a common brain activation network was evident that correlated with IQ. The largest activation in this network was in the bilateral cerebellum.

In another large-scale resting state study, this time consisting of 892 healthy adults recruited from the Brain Genomics Superstruct Project, Saxe et al. (2018) investigated the relation between human intelligence and brain entropy. Brain entropy is defined here as the number of brain states that are accessible for brain functioning and a toolbox is available to calculate brain entropy from resting state fMRI data. Brain entropy was positive associated with intelligence and this relation was strongly observed in the cerebellum (as well as the hippocampus and inferior and frontal lobes).

Structural imaging studies

An early magnetic resonance imaging (MRI) study by Andreasen et al. (1993) was the first to report an association in 67 healthy participants between IQ as measured by the Wechsler Adult Intelligence Scale (WAIS) and cerebellum volume ($r=0.44$). In a follow-up study by the same group with an independent sample, Paradiso et al. (1997) examined relations between cerebellar volume and measures of general intelligence, motor dexterity and verbal/visual

memory. Cerebellar volume showed a positive correlation with motor dexterity and verbal memory and a trend towards a significant association with general intelligence ($p < 0.07$).

Frangou et al. (2004) assessed the relation between general cognitive ability and grey matter volume in 40 children and young adults aged 12 to 21. Cognitive ability was assessed using the WISC and WAIS and cerebellar volume was assessed with MRI. In this study, the cerebellum showed the largest positive correlation between grey matter volume (GMV) and full-scale IQ.

MacLullich et al. (2004) examined the relation between cognitive abilities and cerebellar vermis volume in 50 health men aged 65-70. Significant associations between cognitive tests and cerebellar volume were reported such as an association with Ravens Progressive Matrices, a test closely associated with g and cerebellar GMV ($r = 0.3$).

Hogan et al. (2011) examined the relation between g and grey and white cerebellar matter volume in a sample of 228 older adults. Cerebellar GMV was found to predict g , even after controlling for frontal lobe GM and WM volumes.

In a study of 172 children between the ages of 6 to 13 years taken from the NIH MRI study of Normal Brain Development, Pangelinan et al. (2011) found a significant association between full scale IQ and cerebellar volume.

Taki et al. (2012) examined the correlations between intelligence, body height and brain gray matter volume. The authors found a significant positive association with cerebellar volume, body height and full-scale IQ (after controlling for age, sex, and socioeconomic status).

Brouwer et al. (2014) in a study of 176 monozygotic and dizygotic twins scanned twice over a 5-year period found that cerebellar volume was significantly heritable. In addition a

significant association between IQ and brain volume change was observed, suggested the same genes are involved in cerebellar volume change and intelligence.

Koppelmans et al. (2017) assessed in a sample of 213 older adults, the relation between motor (such as manual dexterity/visuomotor coordination) and cognitive skills (mental flexibility) with cerebellar volume. Significant associations were reported between regional cerebellar volumes and cognitive and motor skills.

In a younger sample of 110 individuals aged from 8-17 years, Moore et al. (2017) found superior performance on g-related tasks (reading, working memory, processing speed) to be associated with greater cerebellar volumes. The study also found a significant age by cognition interaction on cerebellar GMV was found that demonstrated a strengthening positive association across age between GM and cognitive performance.

Yoon et al. (2017) used multivariate statistical techniques to examine covariation between intelligence and cognitive abilities with grey-matter volume networks in 92 healthy adults. A cerebello-parietal network was demonstrated to significantly relate to cognitive performance. However, not all studies investigating the association between g and cerebellar volume have found significant associations (Lange, Froimowitz, Bigler, Lainhart, & Brain Development Cooperative, 2010).

Clinical groups

Early studies such as by Botez et al. demonstrated impairments on IQ tests in patients with cerebellar atrophy, ascertained via CT scans (Botez, Botez, Elie, & Attig, 1989).

Associations have also been demonstrated between cerebellar volume and intelligence in children born pre-term. Allin et al. (2001) found pre-term children to have reduced cerebellar volume compared to matched full-term born controls. There was a significant association

between cerebellar volume and cognitive ability tests such as the Wechsler Intelligence Scale for children. The same group reported that pre-term children demonstrated reduced cerebellar growth compared to matched controls and that this associated with reduced IQ in very pre-term children (J. Parker et al., 2008). This result of reduced cerebellar volume and lower full-scale IQ has been replicated by other groups (Northam, Liegeois, Chong, Wyatt, & Baldeweg, 2011).

Steinlin et al. (2003) reported decrements in intelligence tests following cerebellar tumour removal. This finding has been replicated by other groups (Horska et al., 2010; Puget et al., 2009). In addition IQ impairments have been reported in cerebellar agenesis patients (Timmann, Dimitrova, Hein-Kropp, Wilhelm, & Dorfler, 2003).

Based on these studies, there is clear evidence to support the involvement of the cerebellar as a component of the general factor of intelligence.

The cerebellum and personality

Earlier, I presented evidence supporting the construct of a general factor of personality (GFP). This next section will review evidence associating the cerebellum with personality traits and examine whether there is neuroimaging evidence to link the cerebellum with a general factor of personality. No study to date, has specifically examined an association of the GFP and brain structure or function. Therefore, as a first step to examining the association of the cerebellum with personality traits, I will report on studies looking at lower-order factor traits.

Structural imaging studies

An early study by Matsui et al. (2002) administered the MMPI to 42 university students. An analysis of the schizophrenia-related personality subscale showed a positive correlation of the cerebellum vermis.

Cheung et al. (2010) examined the relation between cerebellar volume and the following questionnaires in 118 adults: the Symptom Checklist-90-R (SCL-90-R), Component of Type A Behavior, the State Anxiety Inventory from Korean YZ, the Sixteen Personality Factor (16PF), and the Self-rating Depression Scale (SDS). A number of associations were reported in the paper. There significant negative associations male phobic anxiety and female hostility (assessed on the SCL-90); between Type A personality and cerebellar volume; a positive association between ego strength (assessed on the 16PF) and cerebellar volume.

DeYoung et al. (2010) looked for correlations between Five Factor personality traits with brain volumes in 116 healthy adult participants. The cerebellum showed a negative association with extraversion and positive correlations with neuroticism and agreeableness. However, only the neuroticism contrast survived multiple comparisons correction.

In contrast to the DeYoung et al. (2010) study, Cremers et al. (2011) found a positive in a study of 65 healthy adults, a positive correlation between extraversion score (derived from the NEO-PI-R) and cerebellum volume.

Hu et al. (2011) also examined the relation between five-factor scores and brain volume in 65 healthy subjects. This time a negative association was found between agreeableness score and cerebellar volume.

Schutter et al. (2012) examined the relation between the trait depression and anxiety scales taken from the NEO-PI-R neuroticism factor and cerebellar volume in 38 healthy male

participants. Significant negative correlations were reported for both depression and anxiety subscale score and total cerebellar volume.

Picerni et al. (2013) examined the relation between personality traits assessed via the Temperament and Character Inventory (TCI) and cerebellar grey and white matter volumes in 100 healthy subjects. A significant positive association was found between novelty seeking score and cerebellar grey matter volume and white matter fractional anisotropy. At an uncorrected statistical level, a significant negative association was found between harm avoidance score and cerebellar volume.

In a study by the same group, Laricchiuta et al. (2014) again examined the relation between cerebellar volumes and TCI scores. Significant associations were found between cerebellar grey and white matter and novelty seeking scores. Significant negative associations were found between harm avoidance and cerebellar grey and white matter.

Lu et al. (2014) examined the relation between brain volumes and personality, using the EPQ in 71 healthy adults. In this study, a positive association was found between cerebellar volume and neuroticism score.

Nostro et al. (2017) also examined relations between Five-factor personality traits and grey matter in a sample of 182 males and 182 female. There were no significant associations with any trait across the whole sample or in the female only group. However, males showed a negative correlation with neuroticism and cerebellar GMV and a positive correlation with extraversion and cerebellar GMV.

In a replication of their earlier study, Schutter et al. (2017) examined the relation of depression and anxiety subscales from the NEO-PI-R Neuroticism factor in 149 healthy volunteers. To extend this research they also included a measure of Behavioural Inhibition.

As before, a significant negative association was found between neuroticism traits and cerebellar volume and this was also present for the measure of Behavioural Inhibition.

Although perhaps not a personality trait as such, Ikeda et al. (2019) conducted a structural imaging study with a very large sample of 1122 participants to assess the relation between self and external preoccupation and brain volume. Self-preoccupation is defined as the tendency to focus more on the self than on others or one's environment and to maintain self-focused attention. In contrast, external-preoccupation is defined as the tendency to maintain external focus on a specific object. However, it is unclear how these traits relate to other personality models. A significant negative association was found between external preoccupation and bilateral cerebellar grey matter volume.

Taken together, studies have reported associations between cerebellar structure and personality traits however no clear pattern emerges. A number of studies have reported associations with neuroticism and related traits such as harm avoidance but both increased and decreased associations have been reported. Similarly for extraversion and related traits such as novelty seeking, both positive and negative associations have been reported. A number of other personality traits have also been examined e.g. agreeableness but again, no clear pattern has emerged.

Functional imaging studies

O'Gorman (2006) conducted a perfusion MR imaging study to investigate the association between Eysenck's and Cloninger's models personality/temperament models and resting cerebral perfusion. Significant positive associations were found between extraversion and novelty seeking scores and bilateral cerebellar perfusion. In addition, a negative correlation was found between Harm Avoidance score and perfusion in the cerebellar vermis.

Hooker et al. (2008) examined how Five-factor personality traits moderated neural correlates of observational fear and reward learning. The cerebellar was activated in a number of experimental contrasts 1) the fear object > neutral object contrast showed a positive correlation between cerebellar activation with agreeableness 2) the learn fear > learn neutral contrast showed a positive correlation between cerebellar activation with openness 3) the learn happy > learn neutral contrast showed positive correlation between cerebellar activation and extraversion and conscientiousness, 4) the happy object > neutral object contrast showed a positive correlation between extraversion and openness.

Coen et al. (2011) examined how neuroticism, as assessed with the Eysenck Personality Questionnaire, moderated brain activation during the experience of visceral pain. Participants in this study underwent fMRI scanning during either the anticipation, or experience of painful esophageal stimulation or rest. A positive correlation was found between neuroticism score and brain activity during both the anticipation and pain conditions.

Kunisato et al. (2011) used resting state fMRI to investigate relations between Five Factor traits and the amplitude of spontaneous low-frequency oscillations (LFO) in 24 healthy undergraduate students. The only trait to show an association with the cerebellum was Conscientiousness that show a negative correlation between trait score and the amplitude of spontaneous LFO.

Wei et al. (2011) assessed the relation between extraversion and neuroticism assessed with the Eysenck personality questionnaire and spontaneous BOLD (Blood Oxygen Level Dependent) activity generated during the resting state. A positive association was observed between extraversion score and spontaneous BOLD activity in the right posterior cerebellum.

Kehoe et al. (2012) examined how personality, again assessed with the EPQ moderated fMRI brain responses to pictures varying in valence and arousal in 23 healthy participants. Participants who scored high in extraversion showed decreasing activation of the cerebellum for pictures rated high in arousal. The authors conclude that this finding is consistent with Eysenck's arousal hypothesis of extraversion (Eysenck, 1963), which proposes that extraverts demonstrate both lower baseline levels of cortical arousal and under-arousability of the cortex, and can tolerate higher levels of arousal better than introverts.

Lawson et al. (2012) investigated how sensation seeking, as assessed with the Brief Sensation Seeking Scale moderated fMRI brain responses to participants completing an old/new object processing task. High sensation seeking participants demonstrated greater responses (compared to low sensation seeking participants) when viewing both new and old objects in the cerebellum compared to baseline. In addition, high sensation seeking participants demonstrated greater cerebellar activity when viewing old compared to new objects (compared to low sensation seeking participants).

Indovina et al. (2014) studied how Five Factor personality traits moderate fMRI responses and functional connectivity to sound-evoked vestibular responses in 26 healthy participants. Neuroticism correlated positively with activity in the cerebellum and connectivity between the cerebellum and amygdala.

In a replication to the O'Gorman (2006) report, Kano et al. (2014) found in 32 healthy adults, a significant positive correlation between resting-state perfusion and extraversion.

In another resting state study, Yin et al. (2016) examined the relation between trait anxiety, assessed with the Spielberger Trait Anxiety Inventory and the amplitude of low-frequency fluctuations in 382 university students. A negative correlation was found between TAI score and spontaneous brain activity in the cerebellum.

Similarly for the structural imaging studies, based on resting-state and activation studies, no clear pattern has emerged between lower-order personality factors and cerebellum functioning. Therefore, given the research base to date, it is not possible at the point in time to reach a conclusion between cerebellar structure and function a general factor of personality.

Cerebellum and psychopathology

There is significant evidence to implicate the cerebellum in the pathophysiology of mental disorders, though space precludes a full overview of this literature. The reader is referred to reviews written on this topic (Baldacara, Borgio, Lacerda, & Jackowski, 2008; Depping, Schmitgen, Kubera, & Wolf, 2018; Lupo, Siciliano, & Leggio, 2019; Miquel et al., 2016; Moreno-Rius, 2018, 2019a, 2019b; Phillips, Hewedi, Eissa, & Moustafa, 2015). Patients with cerebellar lesions, in addition to behavioural and cognitive impairments, have also been documented to present with the signs and symptoms of associated with psychiatric and neurodevelopmental psychopathology (Lupo, Olivito, Siciliano, Masciullo, Bozzali, et al., 2018; Lupo, Olivito, Siciliano, Masciullo, Molinari, et al., 2018; Pesic et al., 2014; Schmahmann, Weilburg, & Sherman, 2007).

Generally, structural neuroimaging studies have also cerebellar structural reductions compared to controls in a variety of disorders covering: addiction-related disorders (Mechtcheriakov et al., 2007; Shen et al., 2018), ADHD (Vieira de Melo, Trigueiro, & Rodrigues, 2018; Wyciszkievicz, Pawlak, & Krawiec, 2017), autism (D'Mello, Crocetti, Mostofsky, & Stoodley, 2015), bipolar disorder (Baldacara, Nery-Fernandes, et al., 2011; D. Kim et al., 2013), depression (Xu et al., 2017), obsessive-compulsive disorder (Narayanaswamy et al., 2016; Tobe et al., 2010), personality disorders (Ermer, Cope, Nyalakanti, Calhoun, & Kiehl, 2013; Zhang et al., 2019), PTSD (Baldacara, Jackowski, et al.,

2011; Holmes et al., 2018), and schizophrenia (Ding et al., 2019; Moberget et al., 2018). However, increased cerebellar volume has also been occasionally documented, such as in social anxiety disorder (Talati, Pantazatos, Schneier, Weissman, & Hirsch, 2013) and antisocial personality disorder (Leutgeb et al., 2015). There is also an extensive literature linking the cerebellum with differences in resting and task-based functional processing in psychopathology (due to space limitations, readers are referred to this literature presented in the above reviews).

Contemporary studies investigating relations between psychopathology and brain-based markers have attempted to go beyond examining single disorders and use neuroimaging to examine similarities and differences across disorders (Mitelman, 2019). With regard to the above discussion of the p-factor as a transdiagnostic psychopathology construct, a number of studies have tested for neural correlates for the p-factor. Romer et al. (2018) conducted the first study to investigate the underlying p-factor neural correlates. In a large sample of 1246 university students, a p-factor was identified and then correlated in a whole-brain analysis with brain grey and white matter volume and integrity. Higher p-factor scores were associated with lower grey matter volume in the cerebellum and lower fractional anisotropy in the pons, the region providing cortical and subcortical input into the cerebellum. Moberget et al. provided a replication of this finding by examining cerebellar volumes collected as part of the Philadelphia Neurodevelopmental Cohort study (Moberget et al., 2019). This cohort consisted of 1401 adolescents aged from 8-23 years. This dataset is valuable as data on general cognitive function was also collected in addition to the collection of neuroimaging and symptom data. In this study, again a negative correlation was found between cerebellar grey matter volume and p-factor scores. In addition, there was a positive correlation between general cognitive functioning and cerebellar volume.

Recently, Romer et al. (2019) reported a non-replication of their original study using participants from the Dunedin birth cohort. Despite replicating the findings of lower fractional

anisotropy in pontine white matter and lower grey-matter volume in the visual cortex, no differences were found in cerebellar grey matter volume. A number of differences exist between this study and the previous two studies. The sample size was lower and the participants were significantly older. Therefore, these two critical variables may have impacted on the findings.

In addition to examining neural correlates of psychopathology and cerebellar structure and function; there is additional evidence implicating the cerebellum in therapies and treatments of mental disorders. Symptom improvement either with natural remission or following pharmacological treatments has been shown to moderate cerebellar activity in depression (Fu et al., 2004; Qin et al., 2015; Walsh et al., 2007; L. Wang et al., 2014), PTSD (Ke et al., 2016), social anxiety (Talati, Pantazatos, Hirsch, & Schneier, 2015), and ADHD (Inci Kenar, Unal, Kiroglu, & Herken, 2017). Magnetic and electric stimulation have been shown to result in symptom improvement in psychiatric disorders (Brady et al., 2019; De Vidovich et al., 2016; Ferrucci, Bocci, Cortese, Ruggiero, & Priori, 2019; Singh et al., 2019) as well as electroconvulsive therapy (Depping et al., 2017; P. Li et al., 2017). Similarly responses to psychotherapy has also been associated with cerebellar changes (MinlanYuan et al., 2017; Rubin-Falcone et al., 2018; X. Wang et al., 2016) and other therapies such as mindfulness therapy (Holzel et al., 2011).

In conclusion, there is substantial evidence linking the cerebellum with psychopathology, and especially a general factor of psychopathology. There is also a link that the cerebellum is a key part of the neural network underlying treatment efficacy, across a wide range of treatments. In the psychotherapy literature there has been a longstanding discussion about a 'common factors' model underlying all forms of psychotherapy (Wampold, 2015), with a key active ingredient of all psychotherapies being the facilitation of cultural adaptation, a process arguably requiring the cerebellum. Relatedly, there have been recent efforts to link this 'Common factors' approach to the general factor of psychopathology presented as part of

the HiToP model (Ruggero et al., 2019). Finally, it's likely that the underlying mechanism of action of other cognitive and behavioural treatments for psychopathology such as psychosocial treatments for schizophrenia and bouldering and dance therapy for depression, also likely recruit the cerebellum (Karkou, Aithal, Zubala, & Meekums, 2019; Lutzenberger et al., 2015; Mueser, Deavers, Penn, & Cassisi, 2013). Therefore, I argue there is clear evidence supporting a general factor of psychopathology and the cerebellum.

Cerebellum and emotional intelligence

The relation between cerebellum and emotional intelligence traits has also been examined. Killgore and Yurgelun-Todd (2007) used fMRI to examine how emotional intelligence moderates the neural response to fearful face processing in 16 children and adolescents aged 8 to 15 years. Emotional intelligence was assessed with the Bar-On Emotional Quotient Inventory. The study found a positive correlation between total EQ score and activity in the left cerebellum. The study also reported another positive association between left cerebellar activity and scores on the interpersonal EQ subscale.

Takeuchi et al. (2011) examined how emotional intelligence related to regional gray matter density in 55 healthy adults. The authors used the Japanese Emotional Intelligence Scale that consists of three factors (Intrapersonal factor, Interpersonal factor and Situation Management factor). In this study, the authors also adjusted for the effects of general intelligence assessed with the Raven's Advanced Progressive Matrices. A negative correlation was found between the Intrapersonal EI factor and grey matter density in the right cerebellum.

Pan et al. (2014) examined how EI moderated spontaneous brain activity using resting-state fMRI. 161 healthy college students participated and trait EI was assessed using the Wong and Law Emotional Intelligence Scale. The WLEIS is comprised of four subscales: (a) self-

emotion appraisal (SEA), (b) others' emotion appraisal (OEA), (c) regulation of emotion (ROE), and (d) use of emotion (UOE). A significant negative correlation was observed between the amplitude of low-frequency fluctuations and EI in the right cerebellum. Subscale analysis showed the cerebellum finding to be present in all subscale comparisons. The results are interpreted as participants high in trait EI demonstrate low spontaneous neural activity in this region.

In another structural imaging study, Tan et al. (2014) examined the association between emotional intelligence and grey matter volume in 328 healthy university students. The measure of EI in this study was the Schutte Self-Report Emotional Intelligence Scale (SSREIS) containing four factors: Optimism/Mood Regulation, Utilization of Emotions, Social Ability and Appraisal of Emotions factors. The study did not examine a general EI factor but a significant positive correlation was found between the Social Ability factor and GMV in the cerebellar vermis.

Taken as a whole, based on the available functional and structural neuroimaging evidence, there is encouraging evidence implicating the cerebellum as important for underlying emotional intelligence traits.

Cerebellum and creativity

Although, as discussed above, no general factor model of creativity currently exists, evidence exists associating this psychological construct with other general factors. It is therefore useful to examine if this construct has also demonstrated cerebellar associations.

Gonen-Yaacovi et al. (2013) provided a meta-analysis of functional neuroimaging studies examining the following keywords “creativity, creative thinking, creative process, unusualness, hypothesis generation, idea generation, aha, eureka, novel ideas, original

ideas, originality, insight problem-solving, insight solution, artistic". The cerebellum came out as a significant region in their global meta-analysis (activations across all studies up to that time) (n=34). It also appeared in all meta-analysis comparisons, activations based on verbal/non-verbal/creative generation/evaluation/unusual uses.

Pinho et al. (2014) used fMRI to examine creative behaviour in the context of musical improvisation during piano playing with 39 professional pianists. The cerebellum emerged during a functional connectivity analysis that examined brain regions for which there was a positive association between improvisation experience and functional connectivity during improvisation. This finding means that participants with greater improvisation experience showed greater functional connectivity between frontal lobe seed regions and the cerebellum during improvisation.

Saggar et al. (2015) created an fMRI version of the game Pictionary and scanned 36 healthy adults whilst they drew pictorial representations of words. The neural correlates of this spontaneous improvisation and figural creativity were contrasted with a control condition of zig-zaw drawing. Compared to the control condition, figural drawing showed marked activations in the cerebellum. In addition, the drawn pictures were then rated for the degree of "creativity" based on scores on three subscales (a) Fluency - total number of elements in the drawing; (b) Elaboration - imagination and exposition of detail; and (c) Originality - the statistical infrequency and unusualness/ uniqueness of the response. Correlating task brain activity with these expert creativity ratings revealed a significant positive correlation located only in the cerebellum.

The same group conducted longitudinal follow-up study to examine how longitudinal creativity building program affected by activity during performance on the Pictionary-based fMRI task (Saggar et al., 2017). In addition to an increase in figural creativity over time in the intervention group, a significant group by time interaction was found in the cerebellum

whereby there was a significant reduction in activity post intervention. There was also an observation of greater functional connectivity between the cerebellum and prefrontal cortex post-intervention. This was interpreted as reflecting (as in improvisation), more “rapid” manipulation of conceptual ideas necessary for making a quick decision.

Schlegel et al. (2015) conducted a longitudinal neuroimaging study to investigate how an activity thought to increase artistic creativity i.e. introductory course in observational drawing or painting moderated brain structure and function. Multivariate pattern analysis (MVPA) was used to distinguish between experimental and control participants based on pattern of brain activity. This MVPA analysis identified demonstrated that cerebellar activity evoked by this drawing task became increasingly separable between art and non-art students over the duration of the art course. This results fits with an earlier study by Chamberlain et al. (2014) that demonstrated greater cerebellar volume to correlate with greater drawing and artistic training in art students.

Feng et al. (2019) used resting-state fMRI to examine the relation between resting-state brain network activity and verbal creativity in 370 healthy college students. The measure of verbal creativity was the Alternative Uses Task (AUT) from the Torrance Tests of Creative Thinking (TCCT) that requires subjects to list as many interesting and unusual uses as possible for a cardboard box using paper and pencil within 10 min. A novel analysis techniques called dynamic network construction and multilayer community detection were used to explore the relationship between dynamic communication patterns among the brain networks and creative performance. The results of this analysis showed that the cerebellum integration with the default-mode network positively correlated with the originality score on the AUT test.

Again, based on the available evidence, there appears clear functional and structural evidence associating the cerebellum with the psychological creativity construct.

Cerebellum and development

Given the above discussion about the evidence for a general factor of development and ageing and the recent evidence that this general factor seems to be fully formed by late adolescence/early adulthood (see (Kremen et al., 2019)), it is worth considering whether there could also be a cerebellar role underlying this general factor of development.

Sowell et al. (2002) studied brain maturation in 35 normally developing adolescents aged between 7 and 16 years. This study found a linear increase in total cerebellar volume with increasing age.

Knickmeyer et al. (2008) examined human brain development from birth until age 2. 85 children were scanned at 2-4 weeks, 35 at year 1 and 26 at 2 years of age. This study found that cerebellum volume increased by 240% over time, with the most rapid growth occurring during the first year. The volume increase was the most of any brain region studied.

Wallace et al. (2006) scanned 90 monozygotic twins, 38 dizygotic twins and 158 unrelated typically developing singletons, aged 5-18 years, to examine regional brain heritability estimates. The cerebellum was notable for showing a distinct heritability pattern, compared to the other investigated cortical grey and white matter regions. The cerebellum demonstrated the lowest genetic effect suggesting strong environmental influences on its development.

Ostby et al. (2009) scanned 171 healthy children, adolescent and adult participants aged 8-30 years. They examined both cerebellar grey and white matter development. For cerebellar grey matter, a linear decrease in volume was observed from over time, white matter showed a quadratic increase over time.

Tiemeier et al. (2010) conducted a longitudinally imaging study focusing specifically on how the cerebellum develops over childhood and adolescence. This study scanned 25 healthy males and 25 healthy females, aged 5-24 years, at least 3 times over 2 year intervals. The cerebellum demonstrated an inverted-U shaped developmental trajectory peaking at age 11 in females and 15 years in males. There was also different regional cerebellar maturation with the cerebellar cortex developing later than the vermis.

Gilmore et al. (2010) examined genetic and environmental contributions to neonatal brain development in 217 neonatal twins. This study comprised 41 monozygotic twins, 50 dizygotic twins and 35 “single” twins – neonates with brain scans unavailable for their co-twins. The heritability of the cerebellum in this study was again low (0.17). The authors compare this study with previous studies and suggest that heritability in the cerebellum increases with age.

Van Soelen et al. (2013) also examined the heritability of the cerebellum in sample of twins scanned at age 9 ($n=190$) and 12 ($n=125$). In this study they also investigated if the same genetic factors that affect height also affect total brain and cerebellar development. This study differed from the Wallace et al. (2006) study by finding a much higher cerebellar heritability estimate of 0.95. Cerebellar heritability estimates increased with age by 4%. There was a significant genetic association between height and cerebellar development ($r = 0.48$). The differences in heritability estimates across studies was proposed as being due to the different participant age ranges across studies.

Wierenga et al. (2014) examined the developmental trajectory of the cerebellum in participants aged 7-24 years of age of whom 53 participants were scanned twice or more. This study replicated the earlier report by Tiemeier et al. (2010) showing a similar inverted-U shaped trajectory across adolescence.

Brouer et al. (2017) examined the genetic influence on cerebellar changes over development and ageing. This study combined five longitudinal twin cohorts from across the world and in different stages of the lifespan. The study estimated that 42% of cerebellar development is due to genetic factors and that heritability estimates were higher in adults than in children, suggesting the brain changes correspond with what has been found in the psychological behavioural genetics literature for IQ (T. J. Bouchard, 2013).

Glass et al. (2018) examined how postnatal infections in newborns born preterm affect brain development and subsequent motor outcomes at 3 years. 219 newborns born preterm at 24-32 weeks of gestational age, with MRI scans both early in life and at term-equivalent age took part in the study. Diffusion-tensor scans and cognitive and motor scales were administered at 35 months of age. Infants with higher postnatal infections had greater cerebellar haemorrhage and this also predicted impaired development of motor pathways and poorer motor outcomes.

Kundu et al. (2018) examined changes in the number of resting-state networks over development in 51 healthy subjects between the ages of 8 to 46 years. The authors found that there was a decrease in the number of network components with increasing age and the cerebellum became increasingly prominent as a hub for integrating these networks. The authors conclude that their results highlight the critical role of the cerebellum in age-related brain connectivity changes.

Maeda et al. (2019) conducted a prospective cohort study to examine in very-low-birth-weight infants, the relation between clinical MRI assessments of brain injury and general movement assessments. The movement assessments were made via video recordings and assessed the complexity, variability and fluency of movements. The results showed that greater cerebellar injury was associated with worse general movement score.

Tan et al. (2019) examined how the effects of smaller cerebellar volumes due to prematurity, affect subsequent behavioural assessments. In this study, a prospective cohort of 109 preterm infants had follow-up 18 months later. Smaller cerebellar volume was associated with specific abnormalities on neurologic examination by 18 months of age, including truncal tone, reflexes, and postural stability. Again, the cerebellum is clearly important for the development of behavioural and psychological functions.

In terms of ageing, Raz et al. (2001) examined the relation between age and cerebellar volume in a sample of 190 healthy volunteers aged from 18 to 81 years. There was a significant negative correlation between age and cerebellar volume suggesting a shrinkage of cerebellar volume of about 2% per decade.

Thus, extensive evidence implicates the cerebellum as a critical region underlying psychological development and ageing. This work informs the work discussed above of how the p-factor relates to cerebellum volume. Development and ageing may confound the association between psychopathology and cerebellar volume.

Fitness and the cerebellum

Zlata et al. (2015) examined the relations between self-reported physical activity, objective aerobic fitness and brain grey matter density. 29 cognitively unimpaired older adults underwent structural MRI scanning and objective (treadmill assessment) and subjective (questionnaire) measures of physical activity and fitness. Higher aerobic fitness was associated with greater grey matter density in the cerebellum only. In addition aerobic fitness moderated the relation between age and cerebellar grey matter density.

Kim et al. (2015) examined how Taekwondo training would affect what they called 'body intelligence' and brain connectivity. Body intelligence referred is defined as awareness and body sensation originated from within the body and the body acting in response to other action or environments (R. Anderson, 2006). 15 children with Taekwondo training were compared to controls (all participants aged 11-12 years) using resting state MRI and with the Body Intelligence Scale. The resting fMRI measures included ALFF and functional connectivity indices. There was significantly greater positive functional connectivity between the cerebellum vermis seed to the right inferior frontal gyrus in the Taekwondo group compared to controls.

Budde et al. (2008) examined in 115 healthy adolescents aged 13-16 years how active coordinative exercise improves attentional performance, assessed via a pen and paper letter cancellation test. Participants were randomly assigned to an experimental or control group and there was a significant group by time interaction with the experimental group performing better following the coordinative exercise.

Demnitz et al. (2017) examined in older adults (mean age 69 years) the relationship between mobility, cognition and cerebellar volume. Mobility was assessed using gain, balance and chair-stands tests, cognitive testing was associated with executive, memory and processing speed tests. Greater cerebellum volume was associated with better mobility.

Talukdar et al. (2018) examined the relation between aerobic fitness (as measured by $VO_2\text{max}$) and individual differences in functional connectivity assessed by resting-state fMRI. 242 healthy young adults underwent assessments of aerobic fitness via a treadmill assessment. This study also assessed fluid intelligence via the Figure Series Test that requires participants to infer rules in a figure sequence. The brain regions having the greatest association with aerobic fitness was located bilaterally in the cerebellum. There was also significant functional connectivity between the cerebellum and middle frontal regions,

fronto-parietal network and ventral attention network. There was also a significant positive association between the fronto-parietal network (of which the cerebellum was part) and fluid intelligence.

Esteban-Cornejo et al. (2019) examined the relation between physical fitness components, brain white matter volume and academic performance in the ActiveBrains project comprising 100 children, aged approximately 8 from the US. The physical fitness components were cardiorespiratory fitness, motor fitness and muscle fitness. Cerebellar white matter volume showed a positive association with the muscular fitness (grip strength). The cerebellum was associated with academic performance but this association did not survive multiple comparisons correction.

Chen et al. (2016) conducted a longitudinal fMRI study to investigate the effects of acute aerobic exercise on working memory performance. 9 healthy children were scanned whilst performing the n-back task before and after a moderate-intensity exercise session. There was a significant reduction in reaction times following the exercise session. Comparison of the post scan vs. pre scan neural correlates demonstrated greater activation in the cerebellum post-exercise. Thus, increased activation in the cerebellum following exercise appeared to enhance working memory performance. This effect appears to mirror the cerebellar and stress-buffering effect of voluntary running found in animal work (Huang et al., 2017), as well as the mechanism of behavioural activation therapy for depressive disorders (Kanter et al., 2010; Veale, 2018).

Again, there seems to be substantial evidence to associated greater cerebellar volume and measures of mobility, coordination and physical fitness.

Cerebellum and social processing

The construct of social effectiveness was discussed above, as was the cerebellum's role ability, personality and psychopathology constructs. Unsurprisingly, the cerebellum is also implicated in social processing. This can mean, both in terms of social processes as a moderator of cerebellar growth and development. It can also cover the cerebellum as a mediator of social information processing and behaviour.

Environmental effects on the cerebellum

Early experimental studies in monkeys showed that growing up in a social environment compared to isolation, was associated with more complex morphology of cerebellar Purkinje cells e.g. (Floeter & Greenough, 1979). Other studies in rats have also demonstrated that early-life stress such as separation and social defeat can affect cerebellar development and motor coordination (Kokubo, Toya, Amano, & Takatsuru, 2018; Kopschina Feltes et al., 2019). Similar effects of prenatal stress have been shown to reduce later Purkinje cell neurogenesis, interneuronal connectivity and behaviour (Ulupinar, Erol, Ay, & Yucel, 2015; Ulupinar & Yucel, 2005; Ulupinar, Yucel, & Ortug, 2006). Badura et al. used chemogenetic perturbations to disrupt development of different cerebellar regions. Disruption of the cerebellar crus I/II regions was associated with reduced social preference behaviour i.e. less time spent with a novel mouse.

Such animal experiments complement findings from human neuroimaging studies. Numerous neuroimaging studies demonstrate that the cerebellum is vulnerable to environmental effects, in a for-better-and-worse fashion. Samples of children exposed to social threat (De Bellis & Kuchibhatla, 2006), deprivation (P. M. Bauer, Hanson, Pierson, Davidson, & Pollak, 2009) and disadvantage (Cavanagh et al., 2013) have reported findings of reduced cerebellar volume compared to controls. This begs the question of how severe exposures need to be to affect cerebellar development. Walsh et al. (2014) found that common family-focused adversities affecting 41% of a population-representative cohort

(Dunn et al., 2011) was associated with reduced medial cerebellar volume. These findings also align with behavioural impairments on cerebellar-associated tasks e.g. saccadic adaptation, balance and motor tasks, following both acute and chronic environmental exposures (Gheorghe, Panouilleres, & Walsh, 2018; McPhillips & Jordan-Black, 2007; Roeber, Gunnar, & Pollak, 2014)

Cerebellum as a mediator of social behaviour

A number of groups have found that in rats, lesions of the cerebellar fastigial nucleus results in significant reductions in activity, open-field exploratory behaviour, and social interactions (D. J. Bauer, Kerr, & Swain, 2011; Behnke, Stevenson, & Swain, 2018; Berntson & Schumacher, 1980). This fits with findings in children with an autism diagnosis showing smaller cerebellar volume was associated with reduced exploratory behaviour and increased stereotyped behaviour (Pierce & Courchesne, 2001). Other animal work using novel optogenetic techniques has implicating the cerebellum in social behaviour (see review by Modi and Sahin (2019)). Very recently, Carta et al. (2019) demonstrated that optogenetic modulation of a cerebellar-VTA projection modulates social exploration in mice.

As discussed above in the context of psychiatric symptomatology, Schmahmann and colleagues e.g. (Schmahmann & Sherman, 1997), have presented cases of patients with cerebellar lesions, termed the Cerebellar Cognitive Affects Syndrome, who also have demonstrated significant social impairments e.g. social judgement and reasoning. Other groups have also found social cognition impairments in cerebellar patients on theory of mind, empathy, decision-making tasks (Clausi et al., 2018; Hoche, Guell, Sherman, Vangel, & Schmahmann, 2016; Roldan Gerschovich, Cerquetti, Tenca, & Leiguarda, 2011).

Neuroimaging studies have implicated the cerebellum in diverse forms of social processing. Studies have found the cerebellum to be implicated in action observation (Sokolov, Gharabaghi, Tatagiba, & Pavlova, 2010), coordinated movement important for group

processes (Chauvigne, Gitau, & Brown, 2014) and processes underlying social cognition (Guell, Gabrieli, & Schmahmann, 2018b), attachment formation (Lee, Walker, Hale, & Chen, 2017) and social reward (Sherman, Hernandez, Greenfield, & Dapretto, 2018). Van Overwalle and colleagues have published extensively, including influential meta-analyses on the role of the cerebellum in social processing (Adamaszek et al., 2017; Baetens, Ma, Steen, & Van Overwalle, 2014; Heleven & Van Overwalle, 2018; Van Hoeck et al., 2014; Van Overwalle, Baetens, Marien, & Vandekerckhove, 2014, 2015; Van Overwalle, D'Aes, & Marien, 2015; Van Overwalle, De Coninck, et al., 2019; Van Overwalle, Heleven, Ma, & Marien, 2017; Van Overwalle, Ma, & Baetens, 2016; Van Overwalle, Manto, Leggio, & Delgado-Garcia, 2019; Van Overwalle & Marien, 2016; Van Overwalle, Van de Steen, & Marien, 2019). The conclusion from this work is that the cerebellum is critically involved in social processing.

Of importance for the discussion on social desirability and social effectiveness, Farrow et al. (2015) investigated the neural correlates underlying social desirability i.e. self-deception and impression-management. Participants were scanned whilst completing the 'Balanced Inventory of Desirable Responding' test (two subscales tapping the self-deception and impression-management dimensions) under either 'fake good' (to give desirable responses) or 'fake bad' conditions (to give undesirable responses). The cerebellum was activated in the impression-management condition (vs. counting baseline) comparison as well as the fake-bad condition (vs. baseline). Thus there is evidence implicating the cerebellum in socially-desirable responding.

Finally, to extend the role of the cerebellum in social processing, comparative evidence exists demonstrating that the cerebellum in part mediates the relationship between play behaviour and later social functioning (Byers & Walker, 1995; Graham & Burghardt, 2010; Joffe, 1997; Kerney, Smaers, Schoenemann, & Dunn, 2017; Lewis & Barton, 2004; Montgomery, 2014; Spinka, Newberry, & Bekoff, 2001).

Part 3: Synthesis

In this review I have discussed integrating general psychological constructs, derived using contemporary psychometric methods, with findings reported in structural and functional neuroimaging studies. General factor constructs discussed have included: intelligence, personality, psychopathology, development, executive functioning, and emotional intelligence. I have also discussed related constructs not yet described using a general factor model, but are nevertheless of interest e.g. creativity. Part 1 outlined these general factors and described psychological-level studies examining their interrelation. Part 2 reviewed available evidence linking general factor constructs with the cerebellum. This next part of the review (part 3) will now synthesise this information and discuss whether there are strong grounds to integrate the cerebellum with these general factor constructs. This then begs the question of if there is an association with across multiple general factors, what does this mean for how psychological constructs relate to the cerebellum? Can we say that all general factors actually relate to the same 'super construct' and if so what does this 'super construct' represent?

With regards to the general factor of intelligence, there is strong evidence, particularly from resting state and structural imaging studies linking this general factor construct to the cerebellum. This evidence becomes stronger with the greater sensitivity provided by larger sample sizes. Regarding the relation of a general factor of psychopathology to cerebellar structure, there are two large-scale studies ($n=1000+$) demonstrating smaller cerebellar volume with higher p-factor score. With regards to the general factor of personality however, no study to date has examined the relation of the GFP construct with neuroimaging and therefore at this time no strong conclusion can be drawn. There have been a number of studies associating lower-order personality traits to cerebellar structure and function, however findings are mixed with no definitive pattern of association. In addition, the sample

sizes are small in comparison to recent imaging studies of other constructs. Nevertheless, given the inverse relation of the GFP and p-factor derived from questionnaire-based studies e.g. (Oltmanns et al., 2018), this would logically follow that higher GFP scores should be associated with greater cerebellar volume. This hypothesis would need to be confirmed in future large scale studies. With regards to the cerebellum and a general factor of development; there is encouraging evidence, especially derived from structural and resting state studies that the cerebellum is a key region underlying neurodevelopmental functional integration. However, more evidence is needed to examine the age at which a general factor of development emerges. Similarly for the constructs of executive functioning, emotional intelligence, creativity and general fitness, evidence increasingly supports the linkage of these constructs with the cerebellum.

What is the construct that can integrate the constructs of intelligence, personality, psychopathology, development, executive functioning, and emotional intelligence, fitness and creativity? One proposal is that assessments of these constructs, either as a trait or ability, require skilled behaviour in a particular domain. Skilled performance is the executing of overlearned and automatic chains of responses. Skills can cover all domains of human experience e.g. social, practical, emotional, intellectual domains. Skills increase our ability to obtain environmental rewards necessary for overcoming environmental challenges and for optimal functioning (Tse, Nakamura, & Csikszentmihalyi, 2019). Skills, can be contrasted with motivation as strategies for obtaining rewards. Motivation being a short-term solution and skilled behaviour a longer term solution (Hikosaka, Yamamoto, Yasuda, & Kim, 2013).

Therefore the cerebellum can be viewed as a neural resource underlying skilled behaviour and psychological flexibility. It can enable cognitive, affective and behavioural adaptation across diverse environmental contexts (Sokolov, Miall, & Ivry, 2017; Spampinato & Celnik, 2018). It has been proposed that the cerebellum is a key region in the formation of internal models representing how organisms interact with their environment (Ito, 2008; Johnson,

Belyk, Schwartz, Pinheiro, & Kotz, 2019; Raymond & Medina, 2018; Wolpert, Miall, & Kawato, 1998). A functioning cerebellum can enable the generalisation of these internal models of behaviour to new contexts in so called context-response linkage (Thach, 1997). Theorists have proposed that the adaptiveness of a model depends upon its correspondence to the actual world (i.e., what is represented has to simulate relevant aspects of the environment); the more complex a working model is, the more flexible are an organism's potential responses (Csikszentmihalyi & Rathunde, 2014; Umpleby, 2009). An argument can also be proposed that, given the links between the cerebellum and creativity, linkage can be made with ideas prominent in evolutionary science thinking, that of creative thought as blind variation and selective retention (Campbell, 1960), a view also gaining prominence in psychotherapy (S. C. Hayes, Villatte, Levin, & Hildebrandt, 2011). In this idea, the cerebellum would be critical for the retention of adaptive patterns of behaviour. To quote from Campbell (1960) "the strategy of organic evolution is to keep a record only of what works, even at the expense of repeating its errors." Thus the cerebellum would keep a record of cognitive and behavioural patterns that have previously proved advantageous, see Cotterill (2001) for a similar argument. Again, this fits with ideas discussed above that psychotherapy involves the modification of context-response relations (Constantino, Bernecker, Boswell, & Castonguay, 2013). It also fits with ideas from developmental science as navigating organism-context relations being a fundamental developmental process (Lerner, 1991).

Carver et al. (2017) have written about the p-factor as representing impulsive responses to emotions. This work reinforces this and expands on this to include the cerebellum. Much work links the cerebellum with impulsivity (Jung et al., 2014; Miquel, Nicola, Gil-Miravet, Guarque-Chabrera, & Sanchez-Hernandez, 2019; Moers-Hornikx et al., 2009; Tessier et al., 2015). To integrate a cerebellar role with the HiToP model (Kotov et al., 2017), it could be reasoned that because of the inverse relation between the 'p-factor' and the GFP, then high scores on the general factor in the HiToP model represent social ineffectiveness. This would

be characterized by the automatic use of maladaptive behavioural coping strategies across varied environmental and social contexts. These strategies may have brought short-term gain in coping with certain early-life contexts in that they may have been solutions to stress-evoking problems experienced earlier in development. However, such strategies prove maladaptive over the longer-term as they do not generalise when applied across varied environmental contexts, hence they prevent a person from growing and become more complex psychologically (Csikszentmihalyi & Rathunde, 2014). This could be termed a person-environment stress-coping mismatch emerging in the transition from childhood and adolescence into adulthood (Homberg, 2012; N. P. Li, van Vugt, & Colarelli, 2017; Schmidt, 2011). This may be a reason why most psychiatric disorders emerge during adolescence (Paus, Keshavan, & Giedd, 2008) as it is a time when adolescents gain independent from the family and more complex forms of social interaction are required. In the evolutionary biology literature, such adaptive coping strategies or traits are known as predictive adaptive responses (Bateson, Gluckman, & Hanson, 2014; Nettle, Frankenhuys, & Rickard, 2013). It would follow then that lower-order components within the HiToP may represent environmentally and developmentally contingent stress-coping strategies helpful for solving a particular problem appearing at early stages of development (Cain, 2019; Fledderus, Bohlmeijer, & Pieterse, 2010). For example, one way to cope with stress may be to regulate eating. In the short-term this could prove effective but in the longer-term would be maladaptive by preventing healthy psychological development and could result in patterns of behaviour being assessed to be characteristic of an eating disorder. The same with substance use disorders, in the short-term they may bring relief, but over the longer-term would be maladaptive and could result in behaviours that fit the signs and symptoms characteristic of substance-use disorders. It remains to be determined whether all HiToP components can be understood in this way.

One causal mechanism for the finding of a smaller cerebellum associated with high p-factor scores, would be the exposure following early life experiences characterised by high social

threat, deprivation and disadvantage. This would lead to the development of less flexible and generalizable predictive adaptive responses. Findings demonstrating smaller structural cerebellar markers from both human and animal studies following exposure to developmental stressors support this (Ulupinar et al., 2006; Walsh et al., 2014). In contrast stimulating and supportive early experiences that require movement variation and generalisation through ‘trial and error’ exploration, is associated with better motor and cognitive development (Hadders-Algra, 2018), a larger cerebellum, and arguably a broader repertoire of predictive adaptive responses (again fitting with the Variation and Selective Retention idea proposed above). This is in effect the Vygotsky ‘zone of proximal development’ concept (Eun, 2017). It is also conceptually similar to Fredrickson’s ‘broaden and build’ model of positive emotions (Fredrickson, 2004). Another concept for integration is the construct of stress-inoculation, whereby exposure to smaller stressors in development allow the formation of necessary stress-coping strategies, necessary for overcoming larger stressors experienced in later life (K. J. Parker & Maestripietri, 2011). In our previous report (Gheorghe et al., 2018), we discuss hypothetical mechanisms underlying stress effects on the cerebellum. Given that theoretical models of cerebellar functioning state that the cerebellum generates and updates internal sensory-motor predictive models of ‘what usually happens’ in order to aid preparation for action, we proposed that that under stress, the updating of cerebellar-internal models is inhibited, either directly via glucocorticoid signalling, or indirectly via the anatomically connected basal ganglia (e.g. through inhibition of reward processes). Future experimental studies are needed to verify this proposed work inhibition effect on cerebellar function. If occurring at vulnerable points in development, this inhibition could impair the growth and maturation of cerebellar structures as previously reported.

One important question pertains to whether there is a common cerebellar computation underlying these general factor constructs. There is a debate currently in the cognitive neuroscience literature as to whether an ontology can be created to explain how mental processes relate to brain systems (Poldrack & Yarkoni, 2016). A similar debate is ongoing in

the psychology literature about concept proliferation and confusion known as the “jingle and jangle fallacies”, the former being the error of referring to different constructs by the same name and the latter the error of referring to the same construct by different names (Lilienfeld et al., 2015). A debate currently exists specifically in the cerebellar literature as to whether the cerebellum performs the same computational function across domains such as a Universal Cerebellar Transform or performs multiple functions consisting of functionally distinct computations (Diedrichsen, King, Hernandez-Castillo, Sereno, & Ivry, 2019; Guell, Gabrieli, & Schmahmann, 2018a). The cerebellum is associated with pretty much all psychological functions and evidence has demonstrated similar topographic organisation to the cortex (Manni & Petrosini, 2004), even to the retinotopic level (van Es, van der Zwaag, & Knapen, 2019). Resolution of this question would then help resolve the question posed here, of whether psychological general factors share a common neuroanatomical basis partly located in the cerebellum. It might also help contribute to the argument as to whether general factor models or other explanations such as reciprocal causation and mutualism can best account for positive manifolds derived from psychometric assessments (van Bork et al., 2017; van der Maas et al., 2006).

These psychological and evolutionary conceptualisations all fit with the idea proposed here that the cerebellum can act as resource enabling behaviour to continually generalise and adapt across varied contexts. The lifespan evidence cited above suggests that this resource is formed by the age of 20 and then forms (Kremen et al., 2019) acts as a cognitive reserve that can be drawn on in later life. It also implies that the greater the resource accumulated via training, from having been in a greater variety of situation previously, then the ease of subsequent cultural and psychological adaptation. Training in limited domains or only in adulthood may not have effects on domain-general cerebellar processes (Sala & Gobet, 2019).

Another issue to discuss is that although these constructs all involve the cerebellum, why are they low correlation between constructs like intelligence and personality? It may be that as others have theorised, the different constructs represent different domains that individuals can invest their time and effort (Ackerman, 2018; C.G. DeYoung, 2011; Kretzschmar et al., 2018; Simonton, 1999; von Stumm & Ackerman, 2013). As discussed above, there have been arguments that a general factor of personality represents a marker of Social Effectiveness (Dimitri van der Linden et al., 2016). With regards to linking the GFP with other broader constructs, Dunkel et al. (2012) examined the relation of the GFP with a measure of Eriksonian psychosocial stages and a measure of Life History strategy (derived from Life History Theory). Life History Theory is a mid-level theory from evolutionary biology that describes the strategic allocation of bioenergetic and material resources among different components of fitness (e.g., calories and nutrients devoted to growth vs. reproduction) (Figueredo et al., 2006). Dunkel et al. (2012) hypothesised, and demonstrated support for the argument that together, these three measures (GFP, Erikson stages and Life History strategy) form a higher order 'Super K-factor'; an even more fundamental higher-order general factor.

A final issue to discuss concerns the processes underlying the formation of any general higher-order factor. For example, in the context of personality, the GFP is the apex of a hierarchical model. However, underlying that are two factors labelled *Stability* and *Plasticity* DeYoung et al. (2006; 2002). Therefore, it is unknown how these two factors interact to facilitate psychological growth and the increase in psychological resources. DeYoung's Stability and Plasticity may correspond to other process theorists have proposed to be critical to the development of the Self, such as Csikszentmihalyi's dialectic between integration (skills) and differentiation (challenges) in his 'Flow' model (Csikszentmihalyi & Rathunde, 2014).

Limitations and future questions

The conclusions read in this article, are exciting and represent a broad integration of diverse psychological constructs. Nevertheless, there are limits to what can be concluded at this point in time and many future questions remain. Thus argument proposed in this article cannot be considered definitive at this point in time. As discussed above, despite extensive evidence to the contrary (see above), the notion of general factors in psychology is not universally agreed. To firmly establish the isomorphism of these general factor constructs, it would require a very large sample of participants to complete psychological, behavioural and physical assessment to derive these general factors. Then this sample would undergo longitudinal neuroimaging to examine how these general factor constructs collectively map onto cerebellar structure, function and developmental change. Given the sample sizes studied in contemporary longitudinal cohort studies such as the Adolescent Brain Cognitive Development Study (n=3434) (Karcher, O'Brien, Kandala, & Barch, 2019), testing this proposal is ambitious but still within the realm of possibility.

Another aspect that has not been discussed, but is critically important is the role of genetics in general factor models. Given the heritability of general factors and to Life History theory this is another important variable to consider. Authors have discussed 'generalist genes' that contribute to multiple psychological phenotypes (Cheung, Harden, & Tucker-Drob, 2015; Eley, 2016; Kovas & Plomin, 2007). Given the heritability of the cerebellum (Brouwer et al., 2014; Z. Li et al., 2018), investigation of whether the same genes are implicated in both psychological and cerebellar markers is of critical importance. It is also of interest to understand the gene-environment-development interplay such as experience-producing drives that may shape general factor and cerebellar development (T. J. Bouchard, Jr., 1997; K. J. Hayes, 1962).

Another limitation to the current review is that many studies do not discuss or actually report their cerebellar findings in the main text. For example the cerebellum showed the greatest

activation on a task of exploratory decision making, however this information is only stated in a supplementary online table (Daw, O'Doherty, Dayan, Seymour, & Dolan, 2006). Thus, there may be other data supporting this hypothesis that exists but did not appear through the current literature search. Thus, the current literature review may actually be an underestimate of the current available evidence.

Conclusions

This review seeks to examine how cognitive neuroscience can inform quantitatively-derived dimensional models of psychopathology classification. This article has sought to integrate the general factor of psychopathology with the other general factor domains, to propose that they all involve the cerebellum. The combination of psychometric population-neuroscience methods has revealed the cerebellum to be a key region underlying this psychological integration. The hope from this article is that this integration will provide a deeper understanding of mental health problems, how they develop and how we can intervene as a society to enhance human functioning.

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