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Genetic and Environmental Influences – PART 2

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Genetic and environmental influences on the phenotypic associations between intelligence, personality, and creative achievement in the arts and sciences

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A B S T R A C T

Several studies suggest a different effect of intelligence and personality on creative achievement in the arts and sciences. There is also research showing that all these variables are influenced by both genes and environmental factors. The aim of this study was to move further and investigate whether the relative influence of genes and environment on the associations between personality, intelligence, and creative achievement differs between the arts and sciences. Measures of intelligence (Wiener Matrizen Test), personality traits (BFI-44), and creative achievement (Creative Achievement Questionnaire) were obtained from a twin cohort. The sample size differed between measures, ranging between 6606 and 9537 individuals (1349 and 2250 complete twin pairs). Firstly, we performed several phenotypic analyses. These analyses collectively showed that intelligence and the personality trait ‘openness to experience’ were the only traits which contributed significantly to achievement, in either creative domain. Intelligence showed a stronger association with science than with art (non-linear and linear form, respectively), while relations between openness and achievement showed the opposite pattern. Secondly, we performed genetic modeling. Univariate analyses showed artistic creative achievement to be the only variable significantly influenced by shared environment. Individual differences in the remaining traits could be accounted for by additive genetic effects and non-shared environment. Results from two trivariate analyses, which included intelligence, openness, and creative achievement in either the arts or sciences, indicated a substantial and fairly equal genetic overlap between openness and achievement in the two creative domains. Genes associated with intelligence however, played a significantly greater role in scientific achievement than in artistic achievement. In fact, the majority of genetic influences on intelligence were also involved in scientific creative achievement. There was also an overlap of unique environmental influences between intelligence and scientific creative achievement that was not present between intelligence and artistic creative achievement.

1. Introduction

Creativity, simply defined as the capability of coming up with ideas that are both novel and useful (Sternberg and Lubart, 1999), is one of the defining characteristics of the human species. With it, we are not only better able to adapt to our environment but also able to adapt our environment to ourselves. In the same vein, humans have a natural capacity for creative thinking, but it is also clear that creative thinking is shaped by our acquired knowledge and experiences. After all, without previously stored concepts and a context, there is no “stuff” out of which to form new ideas, and no frame of reference compared to which they can be identified as either novel or useful. Creative achievements moreover, require sustaining, evaluating, developing, and realizing ideas that are useful given the premises of a certain setting. Thus, manifest creativity is a product of a complex interplay between nature and nurture, something that is indeed the case for essentially all human traits (Nichols, 1978; Polderman, et al., 2015). It might seem like a daunting task to tease out the relative importance of genetic and environmental influences at different stages of the creative process and reveal underlying factors. Nonetheless, this is a very important task to accomplish if we are to find optimal ways to identify talent, foster creative thinking, and maximize creative output for the benefit of both individuals and society.

A commonly used scientific approach for investigating the relative influences of genes and environment on a human trait is to use the classical twin design, which depends on comparing the phenotypic similarity of genetically identical (monozygotic – MZ) and fraternal (di-zygotic – DZ) twin pairs under the assumption that environmental
influences are similar for all twin pairs (Kendler, Neale, Kessler, Heath, & Eaves, 1993). Calculating the difference between the within-pair correlation for MZ twin pairs who share all genes, and DZ twin pairs who share on average half their segregating genes, gives an estimate of the contribution of additive (A) genetic differences to phenotypic variation. Moreover, if the DZ correlation is greater than half the MZ correlation, shared-environment effects (C) are implicated. If the DZ correlation is instead less than half the MZ correlation, dominant (D) genetic effects are indicated. There is however insufficient information in the classical twin design to separate simultaneous influence of C and D. Consequently, an ACE model is generally estimated if the DZ correlation is greater than half the MZ correlation and an ADE model if the DZ correlation is less than half the MZ correlation. The remaining variance is attributed to unknown proportions of non-shared-environment effects plus errors of measurement (E).

The focus of this research article is the genetic and environmental architecture of real life creative achievements in the normal population. In this context, achievement is usually defined as engagement, level of attainment or number of products within certain fields of work (Richards, Kinney, Benet, & Merzel, 1988). The fields of interest typically correspond to a brief list of artistic domains and/or science, based on the intuition that these domains in particular, involve transforming original ideas into valuable products (Carson, Peterson, & Higgins, 2005; Hocevar, 1979; King, Walker, & Bryyles, 1996; Mackinnon, 1962). As an example, Roeling et al. (2017) investigated the heritability of working in a creative (artistic) profession (dance, film, music, theater, visual arts, or writing), using a twin sample. The prevalence of professional artists in the sample was 175/6755 or ~2.6%. The authors estimated the heritability, i.e. A, to 0.56, although power was somewhat limited (95% confidence interval 0.41; 0.80). There was no significant influence of C (estimated to 0.12), perhaps due to lack of power. E was consequently 0.32 (1 – A – C). Excluding C did not decrease goodness-of-fit. The reduced model suggested a larger heritability of 0.70, since variance attributed to C in the full model is picked up by A in the AE model (which means that the estimate of the full model might still be more accurate).

Piffer and Hur (2014) also investigated the heritability of creative achievement in a twin study, but using the Creative Achievement Questionnaire (Carson, et al., 2005). The CAQ measures the level of accomplishment in ten different domains (visual arts, dance, music, theater, humor, writing, architectural design, inventions, science, and culinary). While developing the CAQ, Carson, et al. (2005) performed an exploratory factor analysis and showed that achievements within artistic and scientific domains have higher correlations than between these domains. Piffer and Hur therefore analyzed separately the sum scores for artistic (the first six domains listed above), scientific (the last three domains listed above) and total achievement. The twin sample was fairly small—338 twins. Assuming the same prevalence as reported in Roeling et al. (2017), this means that there would only have been around 9 professional artists included in the sample. The heritability estimates for the three scales were 0.67 (artistic), 0.43 (scientific), and 0.61 (total). The difference between the heritability estimates for artistic and scientific creative achievement did not reach significance. In this study as well, there were no influences of shared environment or dominance, leaving the remainder of the variance accounted for by E.

Thus, research suggests that individual differences in creative achievement can be largely explained by genetic factors and unique individual experiences. Naturally, we would want to take this one step further and reveal more about the identity of those underlying factors. One way to do so is to consider the phenotypic traits that correlate with creative achievement, and investigate to what extent the genetic and environmental influences overlap between the different traits. When it comes to psychological correlates of creative achievement, research has focused primarily on two sources of variance: cognitive abilities and personality (Kandler, et al., 2016). Starting with cognitive abilities, mainly two factors have been explored—intelligence and creative potential.

The notion of ‘general intelligence’ is based on the observation that cognitively demanding psychometric tests tend to correlate (Spearman, 1904). That is, an individual’s average performance on similar tests can be used to predict performance on additional cognitive tests. The latent variable which explains this commonality has been coined the g-factor, which by definition indicates general intelligence (g) (Jensen, 1998). The unspecific nature of g is also reflected in its genetic architecture. The heritability is typically estimated to 0.5–0.9 with cumulative influences from a very large number of genes; in adult samples, influences of shared environment are negligible (reviewed in Bouchard, Bouchard, & McGue, 2003). Consequently, g benefits creative thinking as well as any other more specific cognitive ability. It is therefore not surprising to find that individuals with exceptional creative achievements typically demonstrate high levels of intelligence (Barron & Harrington, 1981; Cox, 1926). The exact role of g and its relation to creativity is however still an intensely studied topic, because it has become apparent that a high g is not sufficient for notable creative accomplishments (Eysenck, 1995). A popular theory, which has found some empirical support, is that beyond a certain threshold of intelligence, other factors such as personality are more important (Jauk, Benedek, Dunst, & Neubauer, 2013). Recent research by Jauk et al. (2014) suggests that intelligence might play a moderating role in converting creative potential into creative achievements. Without in any way questioning these notions, we reason—based on that the predictive power of g increases when tasks are more cognitively demanding (Jensen, 1998)—that intelligence could be viewed as both as a domain general ability which supports most cognitive efforts, as well as a more specific factor for creative thinking and achievement, the importance of which depends on how cognitively demanding creative cognition is in the particular domain of interest. In other words, we propose that the role and importance of general intelligence for creativity is in part domain specific. In support of this, Kaufman et al. (2016) found that intelligence predicts creative achievement in the sciences, but not in the arts.

The second factor ‘creative potential’ is a narrower construct than one might assume, and typically refers only to the ability measured by psychometric divergent thinking tests (Runco & Arar, 2012). Such tests generally feature open-ended multiple solution probes where fluency and originality are the main outcome measures. Factor analyses indicate that all these kinds of tests tap into a single factor, distinct from, although obviously related to, g (McCrae, Arenberg, & Costa, 1987). We have previously argued that this ability would correspond to the second-order factor “long-term storage and retrieval” (Glr) in the Cattell-Horn-Carroll framework, which captures individual differences in fluent retrieval of information through association (de Manzano, Cervenka, Karabianov, Farde, & Ullén, 2010). Divergent thinking scores have been found to correlate with engagement in creative activities and creative achievement, even when adjusting for intelligence (Carson, Peterson, & Higgins, 2005; Jauk, et al., 2014). Similar to intelligence and as proposed by Barron and Harrington (1981), the way divergent thinking relates to creative achievement probably varies from field to field. According to Nichols (1978), the overall heritability and shared environment estimates for divergent thinking are 0.22 and 0.39, respectively, based on the reported mean intraindividual correlations for MZ and DZ twins, averaged across 10 studies.

The discussion on creative personality has revolved primarily around one trait—‘openness to experience’ in the Five Factor Model of personality (FFM) (henceforth referred to as openness) (Digman, 1997). Openness captures a tendency for engaging in and being stimulated by activities that involve intellectual introspection. A person with high openness is generally curious, imaginative, inventive, and likes to reflect and play with ideas; appreciates art and cultivates artistic interests. As could be expected, openness correlates with intelligence around r = 0.33, according to a meta-analysis by Ackerman and Haggsted (1997). The correlation appears to result largely from shared
creative achievement in different domains. Second, there is the genetic and environmental overlap between cognitive abilities, personality, and creative achievement. We may thus formulate a novel research question of whether the genetic and environmental influences on the arts and sciences, found that while scientists were generally less extraverted than non-scientists, more creative scientists were still more extraverted than less creative scientists. It should be pointed out that it was the confidence—dominance facet of extraversion which was prominent in scientists, not sociability. Artists on the other hand, were more distinguished by their socialization scores, which suggested emotional instability, coldness, and rejection of group norms. Kaufman et al. (2016), in the same study as referenced above, reported that openness—unlike intelligence—predicted creative achievement in the arts but not in the sciences. Thus, as in the case of intelligence and creative potential, the importance of personality traits likely varies between contexts (Barron & Harrington, 1981). Twin studies have consistently shown heritability estimates for the FFM personality traits in the range of 0.30–0.60, with little or no effect of shared family environment (Bartels, et al., 2012; Bouchard and Loehlin, 2001).

Thus, general intelligence, creative potential, and personality are important factors for creative achievement. This brings us back to the question of whether the genetic and environmental influences on these underlying traits are shared to some extent with creative achievement. Kandler et al. (2016) analyzed a variety of creativity measures, including self-rated and peer-rated creativity, video-based observer ratings from verbal tests, and figural divergent thinking. The data were obtained from two partially overlapping twin samples that had been tested on several occasions. The sample sizes varied for data acquired in different waves and ranged between ~300 and 1100 twin pairs. In addition to creativity, measures of openness, extraversion, and intelligence were included in the genetic analyses. The results showed that 10%–30% of individual differences in creativity could be accounted for by these three factors. The univariate heritability of perceived creativity (the ratings) where similar across measures (0.27–0.36) while, somewhat surprisingly, no significant genetic effects were found for figural divergent thinking. An influence of shared environment was found for the video-based ratings (0.20) and figural divergent thinking (0.28–0.42, depending on outcome measure). Finally, with regard to the original question, the authors found that the vast majority of the genetic influences on individual differences in creativity scores were shared with openness and intelligence. Though it is not clear what aspects of creativity the self- and peer-ratings actually reflect (potential, personality, achievement etc.), the study certainly confirms the value of multivariate genetic analyses in revealing the causes of covariation between creativity and other traits.

In view of the theoretical background, there appears to be two notions that have yet to be brought together in a genetic analysis. First, there is the specific effect of cognitive abilities and personality for creative achievement in different domains. Second, there is the genetic and environmental overlap between cognitive abilities, personality, and creative achievement. We may thus formulate a novel research question: Do the genetic and environmental influences on the associations between cognitive abilities, personality, and creative achievement differ between creative domains? In order to address this question, we analyzed data from a web survey conducted with the STAGE twin cohort of the Swedish Twin Registry (Lichtenstein, et al., 2006; Magnusson, et al., 2013). Measures of FFM personality, intelligence, and creative achievement were included. No measure of creative potential was available. The work was divided in two parts: First a set of phenotypic analyses, (a) replicating the factor structure of the CAQ and confirming that individuals tend to have achievements either in artistic or scientific domains, but less commonly in both, (b) illustrating the correlational structure and statistical relationships between all included traits and (c) investigating how much variance in creative achievement was explained by each correlate. The second part was contingent on results from the first analyses, and involved modeling the relative influence of genetic and environmental factors on the covariation between creative achievement and its significant correlates (identified in the phenotypic analyses), for the arts and sciences separately.

2. Methods

2.1. Participants

Data were collected from the STAGE twin cohort which is part of the Swedish Twin Registry (Lichtenstein, et al., 2006; Magnusson, et al., 2013), and a web survey conducted between 2012 and 2013. For details on zygosity determination in the Swedish Twin Registry, see Magnusson et al. (2013). Out of the 10,539 twins who participated in the survey (Mosing, Madison, Pedersen, Kuja-Halkola, & Ullén, 2014), we extracted a sample of 9537 individuals (age range 27–54 years, $M = 41 \pm 7.8$ years; 5565 female; 2250 complete twin pairs; 5037 singletons), who had a valid score for at least one of the variables of interest and information on zygosity. The original web survey included an extensive set of questionnaires and experimental tests; participants were free to drop out at any time during the survey and there were indeed dropouts after each module. Therefore sample size in this study varied between measures (see Results). Informed consent was obtained from all participants, and the study was approved by the Regional Ethical Review Board in Stockholm (Dnr 2011/570-31/5, 2011/1425-31, 2012/1107/32).

2.2. Measures

Creative achievement was measured using a Swedish, adapted version of the CAQ by Carson et al. (2005), where participants report involvement and attainment in 7 different domains (visual arts, dance, music, theater, writing, invention, and science). The original CAQ included 10 domains (including also humor, architecture, and culinary) that could be largely represented by two factors—arts and science—in a factor analysis. The adapted CAQ was slimmed in the interest of reducing the overall testing time of the extensive web-survey. More specifically, architecture was excluded because it did not load on either arts or science; culinary had a relatively poor factor loading on science (0.41) and the inclusion of culinary, as well as humor appears to have been mostly arbitrary in the original CAQ (Carson, et al., 2005); and with humor excluded, there remained 5 well-established artistic domains (versus 2 scientific domains).

In the adapted CAQ, similar to the original version, the participant has to respond to the question “How engaged are you in [the domain]” and choose one of seven statements, corresponding to achievement levels. In the original CAQ, the levels are scored 0–7. In the adapted version, the levels were adjusted to match their descriptions better across domains, and are scored 1–7 in order to get a distribution of scores that include individuals with no activity. In the adapted CAQ, the levels indicate (1) no activity; (2) self-taught, no publicly displayed work; (3) taken lessons, no publicly displayed work; (4) publicly displayed work, without monetary reward; (5) publicly displayed work, with monetary reward; (6) professionally active; and (7) professionally active and some work has been recognized nationally/internationally and/or received at least one prize. Scores are summed across all domains and analyzed on an interval scale. It can therefore be noted that someone with low creative achievement in several domains can greatly outperform someone who solely has the highest level of achievement in one domain. The distribution of scores generally has a large positive skew, i.e. there are increasingly fewer individuals at higher levels of achievement (Carson, et al., 2005). As mentioned in the Introduction,
Carson, et al. (2005) performed an exploratory factor analysis of the original CAQ and showed that achievements within artistic and scientific domains have higher correlations than between these domains. For the adapted CAQ, artistic domains were visual arts, dance, music, theater, and writing; the scientific domains were invention and science.

In this study, we invented and explored an additional scoring method of the CAQ that focuses on the maximum achievement obtained across domains. The variable MAX_ART is used to represent the maximum creative achievement level across artistic domains and MAX_SCI represents the maximum creative achievement level across scientific domains. Importantly, only an individual’s highest score in either domain is registered. That is, if the highest achievement is in the arts, the corresponding level/score is represented in MAX_ART, if it is in the sciences, the score is represented in MAX_SCI, and if achievement is equal in both domains, the score is represented in both variables. The rational for exploring this scoring technique is based on the hypothesis that the maximum achievement level constitutes a more accurate estimate of a person’s creativity than the sum of all achievements, since it is practically impossible for someone to devote equal time and interest in all domains. The main domain of interest, and the person’s maximum score, should therefore be more representative of his or her level of creative achievement. The interpretation of the measures is also clearer, since versatility, i.e. being engaged to some degree in several domains, does not contribute to the scores.

Personality data were obtained using the Swedish version of the 44-item Big Five Inventory (BFI) (John, Naumann, & Soto, 2008; Zakrison, 2010). Each item taps one of the five personality factors and consists of a statement with which the participants either agree or disagree by giving a number between 1 and 5. Scores for each factor are then averaged.

Psychometric intelligence was measured using the Wiener Matrizen Test (Förmann & Piswanger, 1979), a timed (25 min) visuospatical matrix reasoning test similar to and highly correlated with the Raven’s Standard Progressive Matrices (r = 0.92). The test consists of 24 multiple-choice items where the number of correct responses is summed to give a total test score.

3. Part 1: the phenotypic data analyses

The aim of the phenotypic analysis was to evaluate the CAQ measure based on the present dataset and explore relations between the CAQ and personality and intelligence in order to inform the genetic modeling. Firstly, we wanted to explore the descriptive statistics, specifically the (non-normal) distribution and the factor structure of the CAQ. For the latter, we performed a principal components analysis (PCA) of raw CAQ scores in all domains. In order to account for relatedness between twins, we performed a split-half analysis, i.e. we split and randomized twins in complete pairs into two groups and then randomly assigned 50% of the singletons to each of these groups, to get two equally sized and unrelated subsamples. The PCA was then performed in each sub-sample. The analysis included a varimax rotation of the normalized factor loadings (raw factor loadings divided by the square roots of the respective communalities). This rotation preserves orthogonality but reorients the dimensional axes to a position that makes the factors easier to interpret since, after rotation, variables will tend to load highly on one factor but low on the remaining factor(s).

Secondly, we examined the correlational structure between the variables of interest: creative achievement, that is, the sum-score for creative achievement in one domain, but higher achievement in the other domains. The variable MAX_ART and the sum-score across artistic domains (EART) and the sum-score across scientific domains (ESCI); the BFI personality factors extraversion (BFI_E), agreeableness (BFI_A), conscientiousness (BFI_C), neuroticism (BFI_N), and openness (BFI_O); and intelligence, as measured by the Wiener Matrizen Test (WMT). We performed a split-half analysis of Pearson product moment partial correlations, adjusting for age and sex, also using a split-half approach. Linear and quadratic relationships as well as two-way interactions between the included variables were explored. The first half of the sample was analyzed to find the most parsimonious and simultaneously best-fitting models for EART and ESCI separately. The models were compared with ANOVA tables. The final models were then replicated in the second half of the sample. The combined results were considered significant if p < .05, two-tailed, in both samples. Thirdly, we investigated the potential differences between artistic and scientific creative achievement with regard to how much unique variance was explained by personality and intelligence. This split-half commonality analysis would depend on the previous analyses and regress EART and ESCI separately on the significant correlates of creative achievement, as well as age and sex. Lastly, to explore the relations between creative achievement and significant correlates, multiple regression models implemented in R were used, where EART and ESCI were regressed on the predictor variables, while adjusting for age and sex, also using a split-half approach. Linear and quadratic relationships as well as two-way interactions between the included variables were explored. The first half of the sample was analyzed to find the most parsimonious and simultaneously best-fitting models for EART and ESCI separately. The models were compared with ANOVA tables. The final models were then replicated in the second half of the sample. The combined results were considered significant if p < .05, two-tailed, in both samples.

3.1. Results of the phenotypic analyses

The descriptive statistics of the variables of interest can be found in Table 1.

The number of participants who scored at each level of artistic and scientific creative achievement are shown in Table 2. Table 2 includes the two variables MAX_ART and MAX_SCI. These variables enable further analysis of for instance the number of individuals who have no achievement in one domain, but higher achievement in the other domain (see Table 2).

The PCA of the CAQ domain-specific scores showed that achievements correlated higher within than across the artistic and scientific domains. The factor loadings can be found in Table 3. The first and second factor, both with eigenvalues > 1 and corresponding to arts and science explained 27% and 19% of the total variance in creative achievement, respectively.

### Table 1

Descriptive statistics of the variables of interest.

<table>
<thead>
<tr>
<th></th>
<th>n</th>
<th>Females</th>
<th>MZ/DZpairs</th>
<th>Min</th>
<th>Max</th>
<th>Mean</th>
<th>SD</th>
<th>Skewness</th>
<th>Kurtosis</th>
</tr>
</thead>
<tbody>
<tr>
<td>ECAQ</td>
<td>6606</td>
<td>3872</td>
<td>706/643</td>
<td>7.0</td>
<td>49.0</td>
<td>11.38</td>
<td>4.13</td>
<td>1.32</td>
<td>2.83</td>
</tr>
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<td>EART</td>
<td>6606</td>
<td>3872</td>
<td>706/643</td>
<td>5.0</td>
<td>35.0</td>
<td>8.03</td>
<td>3.36</td>
<td>1.48</td>
<td>2.95</td>
</tr>
<tr>
<td>ESCI</td>
<td>6606</td>
<td>3872</td>
<td>706/643</td>
<td>2.0</td>
<td>14.0</td>
<td>3.36</td>
<td>1.93</td>
<td>2.00</td>
<td>4.53</td>
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<td>BFI_A</td>
<td>9521</td>
<td>5557</td>
<td>1069/1177</td>
<td>1.3</td>
<td>5.0</td>
<td>3.94</td>
<td>0.47</td>
<td>-0.45</td>
<td>0.46</td>
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<tr>
<td>BFI_C</td>
<td>9521</td>
<td>5557</td>
<td>1069/1177</td>
<td>1.4</td>
<td>5.0</td>
<td>3.91</td>
<td>0.52</td>
<td>-0.40</td>
<td>0.06</td>
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<tr>
<td>BFI_E</td>
<td>9537</td>
<td>5565</td>
<td>1072/1178</td>
<td>1.0</td>
<td>5.0</td>
<td>3.54</td>
<td>0.72</td>
<td>-0.25</td>
<td>-0.32</td>
</tr>
<tr>
<td>BFI_N</td>
<td>9537</td>
<td>5565</td>
<td>1072/1178</td>
<td>1.5</td>
<td>5.0</td>
<td>2.42</td>
<td>0.67</td>
<td>0.38</td>
<td>-0.03</td>
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<td>BFI_O</td>
<td>9521</td>
<td>5556</td>
<td>1069/1176</td>
<td>1.0</td>
<td>5.0</td>
<td>3.27</td>
<td>0.67</td>
<td>0.05</td>
<td>-0.33</td>
</tr>
<tr>
<td>WMT</td>
<td>8242</td>
<td>4806</td>
<td>889/921</td>
<td>0.0</td>
<td>24.0</td>
<td>12.76</td>
<td>5.28</td>
<td>-0.13</td>
<td>-0.54</td>
</tr>
</tbody>
</table>

Values are based on the full sample, including both twin 1 and twin 2. EART = sum of artistic creative achievements, ECAQ = total sum of creative achievements, ESCI = sum of scientific achievements, BFI_A = agreeableness, BFI_C = conscientiousness, BFI_E = extraversion, BFI_N = neuroticism, BFI_O = openness, females = frequency of females, MZ/DZpairs = frequency of monozygotic and dizygotic complete pairs, WMT = Wiener Matrizen Test (intelligence).
Table 2
The frequency and percent of participants at each level of creative achievement.

<table>
<thead>
<tr>
<th>Level</th>
<th>ART</th>
<th>MAX_ART</th>
<th>Diff</th>
<th>SCI</th>
<th>MAX_SCI</th>
<th>Diff</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>N</td>
<td>%</td>
<td></td>
<td>N</td>
<td>%</td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>2133</td>
<td>32.3</td>
<td>1298</td>
<td>19.6</td>
<td>835</td>
<td>39.1</td>
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<tr>
<td>2</td>
<td>1065</td>
<td>16.1</td>
<td>817</td>
<td>12.4</td>
<td>248</td>
<td>23.3</td>
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<td>3</td>
<td>1073</td>
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<td>963</td>
<td>14.6</td>
<td>110</td>
<td>10.3</td>
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<tr>
<td>4</td>
<td>1472</td>
<td>22.3</td>
<td>1351</td>
<td>20.4</td>
<td>121</td>
<td>8.2</td>
</tr>
<tr>
<td>5</td>
<td>563</td>
<td>8.5</td>
<td>512</td>
<td>7.7</td>
<td>51</td>
<td>9.1</td>
</tr>
<tr>
<td>6</td>
<td>214</td>
<td>3.2</td>
<td>207</td>
<td>3.1</td>
<td>7</td>
<td>3.3</td>
</tr>
<tr>
<td>7</td>
<td>86</td>
<td>1.3</td>
<td>86</td>
<td>1.3</td>
<td>0</td>
<td>0.0</td>
</tr>
<tr>
<td>Total</td>
<td>6606</td>
<td>100</td>
<td>5234</td>
<td>100</td>
<td>1372</td>
<td>100</td>
</tr>
</tbody>
</table>

ART = valid responses in artistic domains; Diff = difference between ART/SCI and MAX_ART/MAX_SCI in frequency and percent with ART/SCI as baseline, MAX_ART = valid N in artistic domains, for whom the given level is also the maximum level across all CAQ domains; SCI = valid N in scientific domains; MAX_SCI = valid N in scientific domains, for whom the given level is also the maximum level across all CAQ domains; Δ = the difference between ART/SCI and MAX_ART/MAX_SCI at each level. Values are based on the full sample, including both twin 1 and twin 2.

Table 3
Varimax normalized factor loadings from a principal component analysis of the CAQ domain specific scores.

<table>
<thead>
<tr>
<th>CAQ domain</th>
<th>Factor 1</th>
<th>Factor 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dance</td>
<td>0.60</td>
<td></td>
</tr>
<tr>
<td>Music</td>
<td>0.64</td>
<td></td>
</tr>
<tr>
<td>Theater</td>
<td>0.71</td>
<td></td>
</tr>
<tr>
<td>Visual</td>
<td>0.46</td>
<td></td>
</tr>
<tr>
<td>Writing</td>
<td>0.59</td>
<td></td>
</tr>
<tr>
<td>Invention</td>
<td>-0.03</td>
<td>0.82</td>
</tr>
<tr>
<td>Science</td>
<td>0.16</td>
<td>0.78</td>
</tr>
</tbody>
</table>

Table 4
Pearson product moment partial correlations between creative achievement, openness to experience, and intelligence, adjusting for age and sex.

<table>
<thead>
<tr>
<th>CAQ domain</th>
<th>β</th>
<th>SE</th>
<th>t</th>
</tr>
</thead>
<tbody>
<tr>
<td>ART</td>
<td>0.90</td>
<td>0.20</td>
<td></td>
</tr>
<tr>
<td>MAX_ART</td>
<td>0.61</td>
<td>0.20</td>
<td></td>
</tr>
<tr>
<td>SCI</td>
<td>0.09</td>
<td>0.11</td>
<td>0.03</td>
</tr>
<tr>
<td>BFI_E</td>
<td>0.50</td>
<td>0.26</td>
<td>0.26</td>
</tr>
<tr>
<td>BFI_O</td>
<td>0.24</td>
<td>0.11</td>
<td>0.11</td>
</tr>
</tbody>
</table>

Values are averages based on a split-half analysis for twin 1 and twin 2. Unless specified, correlations were significant at p < .05, two-tailed, in both samples. *Non-significant.

Table 5
Artistic creative achievement regressed on openness to experience and intelligence.

<table>
<thead>
<tr>
<th>CAQ domain</th>
<th>β</th>
<th>SE</th>
<th>t</th>
</tr>
</thead>
<tbody>
<tr>
<td>BFI_O</td>
<td>25.22</td>
<td>1.41</td>
<td>17.94</td>
</tr>
<tr>
<td>BFI_O^2</td>
<td>7.84</td>
<td>0.86</td>
<td>9.17</td>
</tr>
<tr>
<td>WMT</td>
<td>0.08</td>
<td>0.02</td>
<td>5.36</td>
</tr>
<tr>
<td>SEX(f)</td>
<td>0.31</td>
<td>0.03</td>
<td>10.16</td>
</tr>
<tr>
<td>BFI_O:SEX(f)</td>
<td>3.54</td>
<td>0.90</td>
<td>3.84</td>
</tr>
<tr>
<td>BFI_O:WMT</td>
<td>2.05</td>
<td>0.92</td>
<td>2.22</td>
</tr>
<tr>
<td>BFI_O:WMT</td>
<td>-6.68</td>
<td>1.82</td>
<td>-3.68</td>
</tr>
</tbody>
</table>

Table 6
Scientific creative achievement regressed on openness to experience and intelligence.

<table>
<thead>
<tr>
<th>CAQ domain</th>
<th>β</th>
<th>SE</th>
<th>t</th>
</tr>
</thead>
<tbody>
<tr>
<td>BFI_O</td>
<td>0.29</td>
<td>0.03</td>
<td>11.41</td>
</tr>
<tr>
<td>BFI_O^2</td>
<td>-0.43</td>
<td>0.03</td>
<td>-13.57</td>
</tr>
<tr>
<td>WMT</td>
<td>19.73</td>
<td>1.37</td>
<td>14.00</td>
</tr>
<tr>
<td>WMT^2</td>
<td>8.54</td>
<td>0.90</td>
<td>6.47</td>
</tr>
<tr>
<td>BFI_O:SEX(f)</td>
<td>-0.12</td>
<td>0.03</td>
<td>-3.54</td>
</tr>
<tr>
<td>BFI_O:WMT</td>
<td>2.05</td>
<td>0.92</td>
<td>2.22</td>
</tr>
<tr>
<td>BFI_O:WMT</td>
<td>-6.68</td>
<td>1.82</td>
<td>-3.68</td>
</tr>
</tbody>
</table>

‘‘ represents an interaction, BFI_O = openness to experience, SEX(f) = being female, WMT = Wiener Matrizen Test (intelligence). Values are averages based on a split-half analysis for twin 1 and twin 2. Only estimates significant at p < .05, two-tailed, in both samples, are reported.

was excluded from further analysis given its poor predictive value. Hence, we produced separate models for regressing ΣART and ΣSCI on BFI_O and WMT, adjusting for age and sex. The results can be found in Tables 5 and 6.

In order to better understand the relationships illustrated in Tables 5 and 6, we split the dataset according to sex and produced scatter plots of ΣART and ΣSCI as a function of BFI_O and WMT (see Fig. 1). From these graphs, we observe that while females generally score higher on creative achievement in the arts at every level of openness and intelligence, males generally score higher in the sciences. While ΣART is non-linearly related to BFI_O and linearly related to WMT, ΣSCI is non-linearly related to WMT and linearly related to BFI_O.

Since the sample size differed between measures due to drop-out, we additionally explored this dropout with the data available. In the web survey, the BFI was administered before the WMT, which was administered before the CAQ. Between the BFI and the WMT, the dropout was 1297 individuals or 13.6%. The dropout rates for males and females were similar (15.6% and 15.8%). Differences in age and
personality between dropouts and completers were analyzed with t-tests (split-half analyses). The results showed that individuals who dropped out before the WMT, scored relatively higher on extraversion (t(4767) = 2.4, p < .05). Given that extraversion accounted for little unique variance in creative achievement (and was therefore excluded from further analyses) we assume that this difference had little influence on the outcomes in this study. There were no other differences in personality and no age difference between the groups. There were 1636 dropouts between the WMT and CAQ modules (19.8%). Between these modules were a number of extensive experimental tests that seem to have discouraged many participants from continuing the survey. The dropout rates for males and females were similar (26% and 25% respectively). There were no differences in age and no differences in the BFI personality measures between the dropouts and completers at this stage.

3.2. Interim discussion and methodological decisions for the twin modeling

The descriptive statistics confirm that the distributions of the CAQ measures are distinctly non-normal with positive skews. We also confirm that summing achievement scores across domains will likely confound the relation between CAQ and domain general correlates; as indicated in the methods, someone who simply tried 7 domains without further achievement (2 points in each domain = 14 points) will be rated as more creative than someone who has achievement in only one domain but is nationally or internationally recognized (7 + 6 × 1 = 13 points). This can be perceived as counterintuitive. It should also be noted that individuals who report no achievement in one domain, could display higher achievement in another domain. From the frequency table above (Table 2), we observe that 59% of the participants who report no achievement in science, display some achievement in the arts. These individuals can therefore be expected score higher on correlated variables, such as openness, than indicated by their achievement level in science. This effect decreases by the reported level of achievement (see Table 2). One could for instance speculate that investing heavily into one domain leaves less resources for investing into an additional domain (also see Discussion). This additionally means that the correlation between ΣART and ΣSCI is likely lower in high achievers. This should be taken into consideration when evaluating phenotypic and genetic correlations between artistic and scientific creative achievement based on the CAQ (Hur, Jeong, & Piffer, 2014). Further, the differences in shape between the frequency distributions of ΣART and ΣSCI suggest that achievement levels might not be comparable across domains and/or follow a strictly ordinal sequence. We also acknowledge that the top two achievement levels only represent roughly 10% of the sample, while the bottom two levels represent around 40% of the respondents. No transformation of the data (e.g. logarithmic) will really be able to compensate for such a skew, but will merely shift the large block of low-achievers closer to the middle of the distribution. Consequently, any parametric model based on these data will be heavily leveraged by the low-achievers and give worse predictions at the high end of the scale. This problem is exacerbated in the presence of non-linear relationships. For example, consider the association between BFI_O and ΣART illustrated in Table 5 and Fig. 1, panel A. A linear regression model will underestimate the strength of the association between these two variables at higher levels of CAQ, since the model will fit more closely to the majority of individuals, who have lower scores. In other words, previous studies using the CAQ, which did not consider non-linear relationships and that have relied on sum-scores, have presumably been more accurate about the characteristics of low-creative individuals than individuals with high creative achievement.

Clearly, there are complex associations between scientific creative achievement and its correlates. Many of these complexities might emerge as a consequence of treating CAQ as continuous, summing scores across domains and using a parametric statistical model. Thus, we made the following methodological decisions. First, artistic and scientific domains were analyzed separately given the results of the correlation analysis, the PCA, and the commonality analysis. Second, we chose the ‘MAX’-measure over the sum scores for looking at domain specific creative achievement (i.e., where a participant’s score is maintained only if it is also the highest score across all domains; see Table 2). As described in the Methods, the MAX_ART and MAX_SCI variables represent an individual’s highest creative achievement across artistic and scientific domains, respectively, given that the achievement level is also the maximum across both artistic and scientific fields. In other words, only one level is registered for each individual, and assigned to MAX_ART if within the arts, to MAX_SCI if within the sciences, or to both variables if the score is equal in both domains. These
variables are therefore not confounded by the potential of having a higher score in another domain; they are directly linked to maximum achievement within the arts or sciences; and the relations between the MAX-variables and other measures run no risk of being confounded by participants who have higher creative achievement in another domain. Third, we considered the MAX-variables to be on an ordinal scale. Scores are not continuous between levels and the distances between levels are unclear but presumably not equal throughout the entire scale. Fourth, since we chose to treat the MAX-variables as ordinal, this presented an issue with regard to the twin modeling, i.e. that contingency tables in the present dataset between twin 1 and twin 2 for the MAX-variables had several empty cells. Therefore, it was necessary to collapse the levels into fewer bins. An additional benefit of doing so was that it gave the opportunity to reduce the ambiguities regarding the order of levels in the CAQ mentioned above. Thus, we collapsed the CAQ-levels into 4 bins, corresponding to the original levels [1, 2, 3–4, and 5–7], or alternatively [no achievement, self-taught without publicly displayed work, amateurs with formal education and/or publicly displayed work, individuals with professional experience]. This 4-level ordinal measure, which essentially only takes achievement in one domain into account, is a trade down in sensitivity. We would nonetheless argue, in line with the above discussion, that the original sensitivity is to some extent illusory, and the ordinal measure should at the very least give more robust outcomes in statistical analyses. We would also like to point out that contrasting outcomes for MAX_ART and MAX_SCI essentially corresponds to comparing independent groups, since only individuals with the same level of achievement in both the arts and sciences are represented in both domains. The sum-scores are repeated measures, and it is difficult to contrast the arts and sciences domains since there is a different number of subdomains contributing to each score.

It is important to note that the interpretation of the MAX-variables differs from the original CAQ scores and therefore also the conceptualization of creativity. Success in multiple creative domains has in itself been regarded as a marker of exceptional creative ability, which is to some extent incorporated into the original sum scores. The MAX-variables only reflect the maximum achievement, which is either in the arts or in the sciences. A person who is an amateur in many creative domains, remains an amateur. This should be considered when reviewing the results.

### 3.3. Phenotypic results following the methodological decisions

Breakdown tables of the descriptive statistics for MAX_ART and MAX_SCI with regard to BFI_O and WMT can be found in Table 7. Both BFI_O and WMT increase monotonically with MAX_ART as well as MAX_SCI. That is, higher achievement is associated with higher intelligence and higher openness in both the arts and the sciences. This arguably validates that both measures have a distinct order of levels.

Some mean differences in BFI_O and WMT between equal levels of MAX_ART and MAX_SCI can be observed. In order to explore whether these differences between “artists” and “scientists” were significant, we compared them using t-tests (split-half analyses, Bonferroni corrected, excluding individuals with equal achievement in both domains). Scientists had higher intelligence than artists at every level of achievement (amateurs without formal training and public displays: \( t_{(433)} = 2.86, p < .05 \); amateurs with formal training and public displays: \( t_{(1274)} = 6.19, p < .001 \); professionals: \( t_{(614)} = 8.61, p < .001 \). Professional artists had higher openness than professional scientists \( (616) = 6.92, p < .001 \); there were no significant differences at other levels.

Lastly, we reproduced the regression models with the new MAX-variables. Ordinal multiple regression models implemented in R were used, where MAX_ART and MAX_SCI were regressed on the predictor variables, while adjusting for age and sex, using the same split-half approach as for the linear regressions. Compared to the linear regressions with the CAQ sum-scores, there were fewer significant interactions, which could partly be due to lower power. For MAX_ART, there were significant positive effects of openness, intelligence, sex (female), and a negative interaction between openness and sex (female). For MAX_SCI, there were significant positive effects of openness and intelligence and negative effects of age and sex (female). The results can be found in Tables S3 and S4 of the Supplementary material.

### 4. Part 2: the genetic modeling

Based on the phenotypic analyses, MAX_ART, MAX_SCI, BFI_O, and WMT were selected as variables of interest. For the genetic modeling, we used the classical twin design which, as explained in the Introduction, depends on comparing the phenotypic similarity of genetically identical MZ and fraternal DZ twin pairs, under the assumption that environmental influences are similar for all twin pairs (Kendler, et al., 1993). All genetic analyses were performed using structural equation modeling and the CSOLNP optimizer in the OpenMx package (Neale, et al., 2016) in R (R Core Team, 2017). The singletons were included in the estimation of means, variances, and covariance effects. The continuous variables BFI_O and WMT were standardized. The ordinal variables MAX_ART and MAX_SCI were modeled using the liability-threshold approach (Neale & Cardon, 1992). The first two thresholds were fixed (to 0 and 1), which allowed us to estimate means and variances in a similar way to fitting to continuous data (Mehta, Neale, & Flay, 2004). First, we performed univariate genetic modeling of artistic and scientific creative achievement, openness, and intelligence to be able to compare these results with those of previous studies and use them as a reference for evaluating the following multivariate analyses. Secondly, we performed two trivariate ACE Cholesky decompositions, one for each creative domain, with the variables WMT, BFI_O, and MAX_ART/MAX_SCI, in that order. Thus, we assumed that intelligence would not be affected by the other variables and that the remaining two variables were affected by the preceding ones (Neale & Cardon, 1992). At the same time, any genetic or environmental overlap between openness and creative achievement would be adjusted for

### Table 7

<table>
<thead>
<tr>
<th>Level</th>
<th>MAX_ART</th>
<th>MAX_SCI</th>
<th>WMT</th>
<th>MAX_ART</th>
<th>MAX_SCI</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>m</td>
<td>n</td>
<td>SD</td>
<td>m</td>
<td>n</td>
</tr>
<tr>
<td>1</td>
<td>2.78</td>
<td>1297</td>
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<td>1297</td>
</tr>
<tr>
<td>2</td>
<td>3.29</td>
<td>817</td>
<td>0.61</td>
<td>3.23</td>
<td>777</td>
</tr>
<tr>
<td>3</td>
<td>3.35</td>
<td>2314</td>
<td>0.62</td>
<td>3.32</td>
<td>716</td>
</tr>
<tr>
<td>4</td>
<td>3.83</td>
<td>805</td>
<td>0.60</td>
<td>3.51</td>
<td>517</td>
</tr>
</tbody>
</table>

BFI_O = openness to experience, MAX_ART = artistic creative achievement, MAX_SCI = scientific creative achievement, WMT = Wiener Matrizen Test (intelligence). Values are based on the full sample, including both twin 1 and twin 2.
intelligence. The goodness-of-fit (maximum-likelihood) of each of the two models was then compared with reduced models (AE, CE, and E), to determine the most parsimonious model for each creative domain.

### 4.1. Results of the genetic modeling

The estimated twin correlations for the variables of interest are summarized in Table 8. The within-pair correlations of MZ twins were significantly higher than the within-pair correlations of DZ twins for all variables. For WMT and MAX_ART, the MZ correlations were less than twice the DZ correlations, indicating the presence of shared environmental effects and warranting the use of ACE models. For BFI_O and MAX_SCI, the MZ correlations were slightly greater than twice the DZ correlations, which indicated the use of AE models. Frequency tables of MZ and DZ twins (of complete pairs) by the level of MAX_ART and MAX_SCI can be found in Table S5.

While testing the technical assumptions of equality of means and variances across twins and across zygosity groups, it was found that the means and variances of the DZ opposite sex twins could not simultaneously be equated with the other zygosity groups for any of the included variables, indicating potential sex differences. Overlapping confidence intervals between males and females in the twin correlations however indicated low power to detect sex differences (see Table 8). Therefore, the DZ opposite sex twins were excluded and sex was entered along with age as a covariate in all the genetic analyses.

The univariate genetic modeling showed no dominant genetic effects on BFI_O or MAX_SCI, i.e. both these variables could be fit with AE-models, which was also the case for WMT. The heritability, i.e. the proportion of variance explained by genetic factors, was estimated to \( h^2 = 0.68 \) (CI: 0.60; 0.75), \( a^2 = 0.57 \) (CI: 0.53; 0.60) and \( w^2 = 0.59 \) (CI: 0.55; 0.63). For MAX_ART, the ACE-model showed the best fit, with \( A_{MAX} = 0.37 \) (CI: 0.13; 0.63) and \( C_{MAX} = 0.32 \) (CI: 0.06; 0.53). The complete results of the univariate genetic modeling can be found in Table S6 in the Supplementary material.

The model fitting results from the trivariate ACE Cholesky decomposition are summarized in Table 9. There were no significant differences between the ACE and AE models for either creative domain, i.e. there were no significant effects of shared environment in the trivariate analysis on any of the variables of interest. The only variable for which such an effect would have been expected based on the univariate modeling was MAX_ART, but it would seem that power was too low to render it significant in the trivariate analysis. The estimated AE models are illustrated in Figs. 2 and 3. Estimates for the full ACE models can be found in Figs. S1 and S2 in the Supplementary material. The heritability estimates for the variables in the AE models were \( h^2 = 0.69 \) (CI: 0.63; 0.74), \( a^2 = 0.67 \) (CI: 0.59; 0.74), \( b^2 = 0.57 \) (CI: 0.53; 0.61) and \( w^2 = 0.59 \) (CI: 0.55; 0.63) (calculated by adding the squared genetic pathways for each variable, see Figs. 2 and 3). The heritability estimate for MAX_ART was notably higher in the trivariate AE model than in the trivariate or univariate ACE models (0.37), since all variance explained by C in the latter models was picked up by A in the former.

For both domains of creative achievement, most of the covariance with intelligence (artistic: 89%; scientific: 88%) and openness (artistic: 82%; scientific: 85%) could be explained by shared genetic influences. A substantial proportion of the total genetic variance was shared between openness and artistic creative achievement (63%), and between openness and scientific creative achievement (59%). Unique environmental influences were also shared between openness and artistic (24%) as well as scientific (17%) creative achievement. The main difference between the two creative domains/traits appeared to be with respect to the genetic and unique environmental correlations with intelligence. Out of the total variance in intelligence and artistic creative achievement explained by genetic factors, 33% was shared between the two traits. Between intelligence and scientific creative achievement, 58% of the genetic variance was shared, which was significantly higher than for the arts. As for the total variance accounted for by unique environmental factors, 14% was shared between intelligence and scientific creative achievement, while no such influences were shared between intelligence and artistic achievement.

### 5. Discussion

In this study, we investigated the phenotypic relationships between intelligence, openness, and creative achievement; the genetic and environmental architecture of these variables; and whether the relative influence of genes and environment on the associations between these traits differs between the arts and sciences. While both openness and intelligence were correlated with creative achievement in both domains, the correlation between openness and artistic achievement was twice as strong as that between openness and scientific achievement. At the same time, the correlation between intelligence and scientific achievement was more than twice that between intelligence and artistic achievement.
achievement. Since all of these variables display moderate to high heritability, this pattern of correlations indicated that there might also be a different extent of genetic and environmental overlap between openness, intelligence, and creative achievement in the arts and sciences. The results indicated a substantial and fairly equal genetic overlap between openness and achievement in the two creative domains. Genes associated with intelligence, however, played a significantly greater role in scientific creative achievement than in artistic creative achievement. In fact, we show that the majority of genetic influences on intelligence are also involved in scientific creative achievement.

The reason for this domain specificity could potentially be explained based on the following three hypotheses. 1) Creative work can be achieved through a variety of cognitive processes and with different cognitive strategies. 2) Creative work in different fields puts different demands on information processing. 3) Both genetic makeup and life-experiences affect cognitive abilities, personality, and interests, and consequently also the probability of engaging in, enjoying, and excelling at certain (cognitive) activities.

In support of the first hypothesis, we refer to the dual pathway model (Nijstad, De Dreu, Rietzschel, & Baas, 2010; Pinho, Ullén, Castelo-Branco, Fransson, & de Manzano, 2016). This model proposes that creative achievements can be the outcome of either cognitive flexibility, meaning free associative thinking characterized by fluent and flexible switching between semantic concepts, or cognitive persistence, indicating more systematic, effortful and deeper exploration of fewer categories; or a combination of the two. These two strategies are closely linked to the concepts of divergent and convergent thinking. The dual pathway model acknowledges that real life creative achievement can depend, not only on the generative cognitive processes indexed by divergent thinking, but also on more focused, logical and extended convergent thought processes.

We have previously used this model as a starting point for investigating brain activity during creative performance (Pinho, et al., 2016). Using fMRI, professional pianists, and musical improvisation as a model behavior, we found that creative extemporization is the result of a dynamic interplay between several brain regions, and that the patterns of brain activity during creative problem solving depend strongly on the goal of the task and the employed problem solving strategies. Specifically, and in line with the dual pathway model, the results indicated that different task instructions (using a certain set of keys/pitches vs. mediating a certain emotional content) can bias creative cognition towards either of two general cognitive strategies or control modes that to some extent differentiate themselves with regard to brain networks—an expository “intentional” network where the lateral prefrontal cortex exerts top-down control on sensorimotor behavior, and an introspective “free-associative” network, where largely automated processes in specialized brain systems are organized under the influence of the medial prefrontal cortex. This finding has an important implication with regard the second hypothesis because artistic and scientific domains will generally place different demands on expository and introspective processing during creative problem solving. For example—to parallel the conditions of the above experiment—scientific creativity, on average, operates under greater constraint and requires greater top-down cognitive control than does artistic creativity (Simonton, 1999), while artistic creativity, in contrast to scientific creativity, depends more on spontaneous associations, emotional involvement and the expression of affect (Eysenck, 1995; Feist, 1999).

Consequently, since convergent problem solving is associated more with intelligence while divergent thinking is associated more with openness (Sternberg, 1999), the probability for creative success within each of these two domains will be determined by these traits in similar proportions. This, considering the third hypothesis, i.e. that both nature and nurture influence traits and interests which determine motivation and success, should be reflected in the average characteristics of individuals active in each field and more so at higher levels of achievement. This is exactly what we observe in this study and it fits well with what Ackerman and Heggestad (1997) describe in relation to trait complexes; ability level and personality dispositions determine the probability of success in a particular task domain, and interests determine the motivation to attempt the task. Subsequent to successful attempts at task performance, interest in the task domain may increase. Conversely, unsuccessful attempts at task performance are likely to result in a decrement in interest for that domain. Thus, the development of personality-interest-intelligence traits tends to involve mutual causal
influences between traits, creating different trait complexes in different fields of endeavor. In conclusion, we propose that artists and scientists, on average, exhibit trait complexes of openness and intelligence that match the usefulness of these traits in the main creative problem solving strategy in each domain. These traits are therefore not only to be viewed as domain general traits which indirectly promote creativity, by increasing creative potential or moderating the realization of creative potential into creative achievements, but also as traits that can be intimately associated with creative thinking processes per se, depending on the cognitive approach. This could also explain why we find an overlap of unique environmental influences between intelligence and scientific creative achievement but not between intelligence and artistic creative achievement. Environmental factors that decrease intelligence would directly impede the cognitive control processes involved in scientific creative achievement, but not necessarily limit the free associative processes involved in artistic creative thinking to the same extent.

Openness and intelligence are presumably not the only traits that are important in this context, but certainly the ones that have been studied the most in the past. It would be interesting in future studies to also include measures of creative potential/divergent thinking, as well as of perceptual and aesthetic abilities which also appear to have substantial heritability (Barron & Parisi, 1976), in order to find traits with high genetic correlations with artistic creative achievement. It might seem curious that other than openness, the FFM personality traits appear to have no influence on creative achievement. One explanation for this is that the FFM cannot account for the often complex nature of the creative personality. Creative individuals, particularly in artistic fields, are often characterized by their strong and often eccentric personalities (Feist, 1999). As described by Csíkszentmihályi (1997), what signifies highly creative individuals is often an ability to express a range of traits either at the same time or at different times, depending on the situation; an ability to move from one extreme to the other as the occasion requires. For example, displaying a combination of playfulness and discipline, or extreme work morale together with a blatant disregard for rules and authorities, or inner-directed reflection at one time and intense social interaction at another. These contradictory extremes might simply average out in the FFM.

A notable difference between artistic and scientific achievement is the substantial influence of shared environment for artistic creative achievement, as was shown in the univariate genetic analysis. Participation in cultural activities is common among children in Sweden and is encouraged by both schools and parents. For example, 60% of fifth graders report playing a musical instrument, 28% practice dance and 16% theater; 40% participate in music/cultural school activities in their free time (Myndigheten för kulturanalys, 2017). Clearly, most children are exposed to cultural activities from an early age and it would appear that this has an effect on later creative achievement. Similar statistics on scientific activities are not available, which is in itself an indication that such leisure activities are less common and not particularly promoted by schools or the government in Sweden. This and the importance of intelligence is presumably why scientific achievement was found here to be driven exclusively by genetic and unique environmental factors. Some shared environmental factors, e.g. parental support, could also be expected to correlate with relevant genetic factors. Parents working in a scientific domain might for instance to a higher degree support scientific interests in their children. Since such exposure would correlate with inherited genetic factors, the effect of it would make MZ twins even more similar than DZ twins and therefore be interpreted as genetic influences in the genetic analysis. A limitation in this study, as in any other study on achievement that is based on random sampling in the general population, is the comparably few individuals to be found at the highest levels. As previously discussed in relation to the phenotypic analysis, this creates a number of issues with regard to the statistical analysis. Here, we traded off sensitivity, by collapsing the CAQ into 4 levels, for a more robust statistical approach. Having access to an even larger sample of twins might present other opportunities, which also include studying sub-domains and potential sex differences, for which power was too low in the present case. With a larger sample, we would also have expected a significant effect of shared environment on MAX_ART in the trivariate analysis, in the range of what was shown in the univariate analysis. The power to accurately detect the shared environmental effects generally requires very large sample sizes (Visscher, Gordon, & Neale, 2008). Moreover, the composition of the present sample was not ideal for finding shared environmental effects given the relatively large proportion of MZ to DZ twins. The optimum proportion will vary with the “true” model of variation but is most likely to be between 2/3 and 1/2 of DZ twin pairs (Martin, Eaves, Kearsey, & Davies, 1978; Visscher, 2004). As the proportion of MZ to DZ twins increases, the probability of finding additive genetic effects increases and the probability of finding shared environmental effects decreases.

It would be interesting to learn more about why females generally score higher on creative achievement in the arts at every level of openness and intelligence, while the opposite is true for scientific achievement. The explanation may involve sex differences in traits and/or cultural factors (Wang & Degol, 2017). We would also encourage research on how to optimally deal with the issues concerning how to measure and score creative achievement and there are certainly ongoing efforts; a promising recently developed instrument is the Inventory of Creative Activities and Achievements, which unlike the original CAQ, use the same levels of attainment in each domain (Diedrich, et al., 2017). The question remains however, how to best score creative achievement across domains. Here we argue that the MAX-measure is superior to using sum-scores.

Lastly, we would like to highlight the complex domain-specific relations illustrated in the phenotypic analyses between intelligence, openness, and creative achievement in the arts and sciences. The notion that associations between measures of creativity and underlying traits can take on different (linear/non-linear) forms in different domains, is rarely accounted for in empirical studies, and has in our view not been explored enough. The threshold hypothesis (mentioned in the Introduction) which states that the effect of intelligence is attenuated at higher levels of creative achievement, might for instance not apply to science.

Funding

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Acknowledgements

We thank Dr. Miriam Mosing, Dr. Karin Verweij, and Dr. Rita Almeida for consultations on the genetic modeling and statistics and Dr. Laura Babcock for reviewing the manuscript.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.intell.2018.05.004.

References

Ackerman, P. L., & Heggestad, E. D. (1997). Intelligence, personality, and interests: Evidence for overlapping traits. Psychological Bulletin, 121, 219-245.
Köcher, T. J., Jr., & McGue, M. (2003). Genetic and environmental in...
**INSTRUCTIONS**

- Read through the article and answer the multiple-choice questions provided below. There is only ONE CORRECT ANSWER TO EACH QUESTION.

---

**Question 1:** Which variable was NOT a variable of interest based on the phenotypic analyses?

A: MAX_ART  
B: MAX_SCI  
C: BFI_O  
D: WMT  
E: The g factor

**Question 2:** Is the following statement TRUE or FALSE?  “The correlation between openness and artistic achievement was twice as strong as that between openness and scientific achievement?”

A: TRUE  
B: FALSE

**Question 3:** Genes associated with intelligence played a significantly greater role in what type of creative achievement?

A: Artistic  
B: Scientific  
C: In both artistic and scientific achievement

**Question 4:** What type of model supports the first research hypothesis, namely that creative work can be achieved through a variety of cognitive processes and with different cognitive strategies?

A: The single pathway model  
B: The double pathway model  
C: The dual pathway model

**Question 5:** Which one of the following statements is FALSE with reference to this model?

A: Creative achievements can be the outcome of either cognitive flexibility or cognitive persistence  
B: Cognitive flexibility means free associative thinking characterized by fluent and flexible switching between semantic concepts  
C: It acknowledges that real life creative achievement can also depend on more focused, logical and extended convergent thought processes  
D: It has not been used as a starting point for investigating brain activity during creative performance

**Question 6:** These two strategies are closely linked to the concepts of which types of thinking?

A: Creative thinking  
B: Divergent thinking  
C: Convergent thinking  
D: A and B  
E: B and C

**Question 7:** The researchers found that creative extemporization is the result of a dynamic interplay between several brain regions through which test?

A: CT  
B: MRI  
C: fMRI  
D: PET

**Question 8:** Which type of creativity operates under greater constraint and requires greater top-down cognitive control?

A: Artistic creativity  
B: Scientific creativity  
C: General creativity

**Question 9:** Is the following statement TRUE or FALSE?  “Artistic creativity depends more on spontaneous associations, emotional involvement, the expression of affect as well as top-down cognitive control?”

A: TRUE  
B: FALSE

**Question 10:** Which one of the following is associated more with intelligence?

A: Creative thinking  
B: Divergent thinking  
C: Convergent problem-solving

**Question 11:** What type of thinking is associated more with openness?

A: Creative thinking  
B: Divergent thinking  
C: Convergent thinking

**Question 12:** Is the following statement TRUE or FALSE?  “Ability level and personality dispositions determine the probability of success in an articular task domain, and interests determine the motivation to attempt the task”

A: TRUE  
B: FALSE

**Question 13:** What type of factors that decrease intelligence would directly impede the cognitive control processes involved in scientific creative achievement?

A: Personality factors  
B: Genetic factors  
C: Environmental factors
Question 14: Is the following statement TRUE or FALSE?
“It appears that children who are exposed to cultural activities from an early age show greater creative achievement later on?”

A: TRUE
B: FALSE

Question 15: Fill in the missing words correctly: As the proportion of MZ to DZ twins increases, the probability of finding additive genetic effects ....... and the probability of finding shared environmental effects .......

A: Increases; decreases
B: Increases; increases
C: Decreases; decreases
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