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The Nature of Creativity: The Roles of Genetic Factors, Personality Traits, Cognitive Abilities, and Environmental Sources

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This multitrait multimethod twin study examined the structure and sources of individual differences in creativity. According to different theoretical and metrological perspectives, as well as suggestions based on previous research, we expected 2 aspects of individual differences, which can be described as perceived creativity and creative test performance. We hypothesized that perceived creativity, reflecting typical creative thinking and behavior, should be linked to specific personality traits, whereas test creativity, reflecting maximum task-related creative performance, should show specific associations with cognitive abilities. Moreover, we tested whether genetic variance in intelligence and personality traits account for the genetic component of creativity. Multiple-rater and multimethod data (self- and peer reports, observer ratings, and test scores) from 2 German twin studies—the Bielefeld Longitudinal Study of Adult Twins and the German Observational Study of Adult Twins—were analyzed. Confirmatory factor analyses yielded the expected 2 correlated aspects of creativity. Perceived creativity showed links to openness to experience and extraversion, whereas tested figural creativity was associated with intelligence and also with openness. Multivariate behavioral genetic analyses indicated that the heritability of tested figural creativity could be accounted for by the genetic component of intelligence and openness, whereas a substantial genetic component in perceived creativity could not be explained. A primary source of individual differences in creativity was due to environmental influences, even after controlling for random error and method variance. The findings are discussed in terms of the multifaceted nature and construct validity of creativity as an individual characteristic.

Keywords: perceived creativity, tested figural creativity, personality, intelligence, multitrait multimethod twin study

Creativity is a crucial driving force spurring progress and civilization. Most of our prosperity and wealth is attributable to creative persons' inventive and beneficial ideas at some point in human history (Runco, 2004). Thus, there has always been a strong interest in psychological research on creativity (e.g., Eysenck, 1995; Guilford, 1950; Simonton, 2003b). This research varies as a result of diversity in definitions of creativity, theories, and methods of measurement.

Here, we investigated creativity from different perspectives and added a behavioral genetic approach to gain new insight into the structure and sources of creativity. We first highlighted creativity from different theoretical and empirical points of view. Second, we

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The present research used data from two German twin studies—the German Observational Study of Adult Twin (GOSAT) and the Bielefeld Longitudinal Study of Adult Twins (BiLSAT)—which were both conducted at the University of Bielefeld. GOSAT was supported by a grant from the German Research Foundation (Deutsche Forschungsgemeinschaft: AN 106/13-1) to Alois Angleitner, Peter Borkenau, and Rainer Riemann. BiLSAT was initiated by Alois Angleitner, Rainer Riemann, and Frank M. Spinath as a joint research project with funding from the Max Planck Research Prize awarded to Alois Angleiter. In addition, many other investigators contributed to both studies. We thank the whole GOSAT and BiLSAT research teams as well as the twins for spending part of their lifetime with both study projects. We are also indebted to the many experimenters for collecting the data, in particular to Simone Penke and Anna-Karen Stürmer for their help in rating the T-88 creativity test data. Finally, we thank our master's candidate students, Katharina Buchenau, Miriam Horneber, Rebecca Kniep, Kirsten Metzger, Ruth Nahrgang, Tiago Schmidt-Riese Nunes, Valeska Stephan, and Kerstin Vogler, for their important contributions to the current study.

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examined different aspects of creativity using multiple methods of measurement (tests, observations, and questionnaires) and multiple informants (self, peers, and observers). Third, we analyzed how these different aspects are associated with intelligence and other core traits, such as openness to experience and extraversion. Fourth, we investigated the genetic and environmental sources of individual differences in creativity using genetically informative (and environmentally sensitive) twin data. And finally, we examined to what degree genetic sources of variance in creativity aspects could be accounted for by genetic variance in verbal and nonverbal intelligence, openness to experience, and extraversion.

Theoretical Perspectives

Creativity as Product and Process

Despite common agreement that Einstein, Mozart, Darwin, Picasso, and Steve Jobs are prototypical creative persons, it is quite hard to describe individual differences in creativity. There is no explicit and common definition of creativity or what it consists of. On the one hand, individuals' creativity can be assessed by the quantity and quality of their products, which have to be *original* (innovative, novel, or highly unusual) and *useful* (problem-solving, fitting, or adaptive) for one's own life, a group of others, or even the entire society (Barron, 1955; Mumford, 2003; Stein, 1953). Because the originality and the utility of a product depend on the zeitgeist and evaluation by the social context, creativity can be assessed with ratings on observable products with high interrater consensus (Amabile, 1982).

On the other hand, it has been emphasized that a creative product may reflect an innovative and problem-solving idea that does not have to get realized completely in observable products (Mackinnon, 1962; Prabhu, Sutton, & Sauser, 2008). Moreover, processes of elaborative and problem-solving thinking, as well as acting, may be creative (Smith, Ward, & Finke, 1995). Thus, researchers have focused not only on products to assess creativity but also on the cognitive processes leading to them, such as rather chaotic associative and attentional processes (e.g., Mendelsohn, 1976), analytic-logical thinking based on problem-relevant expertise (e.g., Weisberg, 1986), or an efficient alternation between unsystematic or defocused and systematic or focused cognitive processes (e.g., Campbell, 1960; Simonton, 2011a, 2011b).

Creativity as an Individual Characteristic

The term *creativity* may also refer to relatively stable behavioral traits and cognitive abilities that are most characteristic for creative persons (Guilford, 1950). According to the characteristics of creative products, creativity can be described as a more or less stable and more or less contextualized ability to develop novel and appropriate ideas and products (Sternberg & Lubart, 1999). According to the cognitive processes relevant to the production of innovative and problem-solving products, creativity may subsume diverse individual differences, such as variation in cognitive flexibility and capacity, efficient utilization of knowledge, open-mindedness, or the attentional orientation to nonassociative and apparently problem-irrelevant external stimuli. These characteristics allow new associations of experiences and enable innovative ways to solve problems. They may all reflect different aspects of creativity.

(Re)Sources of Creativity

In their investment theory of creativity, Sternberg and Lubart (1991, 1992) argued that the creation of innovative and useful products requires a confluence of six resources: intelligence, knowledge, thinking styles (i.e., preferences of specific ways of information processing), personality traits (e.g., tolerance of ambiguity, willingness to grow, risk-taking boldness), intrinsic motivation, and supportive environment. Although the environment sets the contextual conditions (e.g., positive innovation climate, stimulating milieu, absence of evaluation pressure) to foster creativity, the other five components can be treated as relatively stable and less contextualized internal, personal, or individual characteristics (rather than resources).

The role of personality traits and intelligence has been emphasized by many other researchers (Barron & Harrington, 1981; Guilford, 1950; Simonton, 2014). Individual differences in tolerance of ambiguity and willingness to grow, as well as cognitive flexibility, fantasy, open-mindedness, and having broad interests in several issues (e.g., science, arts, and aesthetics), can be economically described in terms of *openness to experience*. This personality trait is characterized by breadth, depth, and permeability of consciousness, and involves preference for variety, intellectual curiosity, and enduring need for novelty and new ideas to enlarge knowledge and expertise (Denissen & Penke, 2008; Goldberg, 1993; McCrae & Costa, 1997). Moreover, openness is conceptually and empirically associated with a wide array of specific, intrinsically motivational characteristics, in particular, cultural-intellectual and artistic-creative interests (Barrick, Mount, & Gupta, 2003; Kandler, Bleidorn, Riemann, Angleitner, & Spinath, 2011; Larson, Rottinghaus, & Borgen, 2002). Not surprisingly, openness has been conceptualized as the core trait underlying creativity (McCrae, 1987).

Risk-taking behavior and an orientation to diverse external stimuli are facets of *extraversion*. This personality trait encompasses the general tendency to seek stimulation, orient attention to external stimuli, and enjoy social attention and interaction (Ashton, Lee, & Paunonen, 2002; Denissen & Penke, 2008; Eysenck & Eysenck, 1985), which allows various impulses for creative thinking and, thus, for innovative products. In addition, extraverts may tend to express and share their innovative ideas with their social context more so than introverts. Thus, they may also be perceived by others as more creative than introverts.

The creation of innovative *as well as* useful products also requires a logical and systematic analysis, selection, and integration of ideas that can be facilitated by the availability and the utilization of relevant skills and expertise (Gabora, 2011; Simonton, 2010; Sternberg, 2006). The construct *intelligence* as general cognitive ability comprises reasoning, mental speed, as well as the ability to conceptualize and to gain, structure, retain, and use knowledge. Thus, high intelligence should positively contribute to generating creative products.

What makes a person more creative than others? The answer may be that creative people are open to experience, somewhat extraverted, and intelligent, and they have problem-relevant expertise and a supportive environment. Whereas the personality traits *openness* and *extraversion* as relatively stable patterns of typical thinking, feeling, and acting can facilitate typical creative thinking and behavior, *intelligence* can be seen as rather stable general cognitive ability contributing to maximum creative test performances. In addition, the social context is very important, because it evaluates and fosters creativity.

Empirical Perspectives

Creativity and Personality Traits

Many studies have found correlations between specific personality traits and creativity (Batey & Furnham, 2006; Feist, 1998). The most robust link is the positive correlation between openness and creativity, which ranges between $r = .20$ and $r = .50$ depending on the operationalization of creativity and the variety in samples (e.g., Furnham, Batey, Anand, & Manfield, 2008; King, Walker, & Broyles, 1996; McCrae, 1987; Silvia, Nusbaum, Berg, Martin, & O'Connor, 2009). Soldz and Vaillant (1999) used a longitudinal study design and found correlations between openness and creativity of $r = .40$ over a 45-year time span.

The findings on the relationships between creativity and other personality traits are less consistent. Beyond openness to experience, extraversion appears to be the most robustly associated personality trait. Several studies have reported positive correlations between extraversion and creativity across different measurement methods (e.g., Furnham & Bachtiar, 2008; Furnham, Crump, Batey, & Chamorro-Premuzic, 2009; King et al., 1996).

Based on a moderate correlation between openness and extraversion, some researchers have integrated both traits into a higher order personality factor called *plasticity* (DeYoung, 2006; Digman, 1997; Riemann & Kandler, 2010). Studies have found at least moderate correlations between plasticity and creativity (Peterson, Smith, & Carson, 2002; Silvia et al., 2009). Moreover, plasticity was found to be negatively associated with latent inhibition, a preconscious cognitive mechanism that allows a person to ignore stimuli that are familiar or that have previously been categorized as irrelevant (Peterson & Carson, 2000). This is noteworthy because low latent inhibition, which entails that various unfiltered stimuli enter awareness, and increases the sensitivity to seemingly unrelated cues to the solution of a problem, has been discussed and shown to be associated with a number of diverse creative accomplishments (Carson, Peterson, & Higgins, 2003; Kéri, 2011; Martindale, 1999). Thus, openness and extraversion may contribute to the quantity and diversity of innovative ideas and creative activities (e.g., composing music; painting or modeling arts; writing songs, poems, or stories; designing programs for marketing or training; gardening; tailoring).

Creativity and Cognitive Abilities

Designing innovative and useful products also requires high cognitive capacity and efficient utilization of knowledge. Working memory capacity has often been discussed and supported as a substrate of intelligence (see Kane & Engle, 2002, for a review), which has been considered as a necessary requirement for the analysis of novel ideas to identify the most useful idea (Simonton, 2011a; Sternberg, 2006).

The relationship between creativity and intelligence is still a widely studied issue. Correlation studies revealed at least modest associations of between $r = .20$ and $r = .40$ (e.g., Batey, Chamorro-Premuzic, & Furnham, 2010; Batey & Furnham, 2006; Nusbaum & Silvia, 2011; Preckel, Holling, & Wiese, 2006; Silvia & Beaty, 2012), indicating that intelligence may be seen as a prerequisite of creativity. Importantly, intelligence has been found to be a predictor of creative achievements, but not creative activities, as well as a moderator of the relationship between creative activities and achievements. This highlights the role of intelligence as a filter of creative output, supporting its transformation into useful products (Jauk, Benedek, & Neubauer, 2014).

Although most studies have focused on a general factor of cognitive abilities or reasoning, fewer studies have focused on knowledge. The empirical evidence for a potential influence of knowledge on creativity is inconsistent. Whereas some studies reported negligible influences beyond effects from intelligence (e.g., Batey, Furnham, & Safiullina, 2010), other studies found effects comparable with general intelligence (e.g., Sligh, Conners, & Roskos-Ewoldsen, 2005). The incremental effect of knowledge on creativity beyond general intelligence may depend on its utility with respect to the specific task or problem. Similarly, studies suggest a lower effect of intelligence on creativity when the effect of openness is controlled (e.g., Silvia, 2008).

Metrological Versus Substantive Aspects

The empirical inconsistency across studies regarding the links between creativity and personality traits, or between creativity and cognitive abilities, may in part be due to the measurement of creativity. For example, Batey and colleagues (2010) found that intelligence was significantly related to creativity test scores and observer ratings on test performance, but showed negligible associations with self-rated creativity and everyday creative behavior. On the other hand, openness was primarily associated with the creativity self-concept and everyday creative behavior, but showed weaker links to test performance (see also Furnham et al., 2008, and Silvia et al., 2009). Because personality traits are typically captured by self- and observer ratings, whereas intelligence is typically measured with cognitive performance tests, it may not be surprising that self-rated or observed creativity is associated with personality trait ratings, whereas creativity test scores show links to intelligence test scores.

This metrological dualism, however, may not necessarily reflect an artifact. Creativity may include different substantive aspects, such as typical creative behavior and everyday creative activities, as well as maximum creative performance in specific tasks (e.g., figural-creative or verbal-creative performances). Openness and extraversion may affect the quantity and diversity of everyday creative engagement, whereas intelligence may have an influence on the maximum performance in creative activities and the quality of the creative productions. Typical engagement in creative activities can be rated with more accuracy by the target persons themselves and well-informed others (e.g., peers) than by less-informed others with limited observations in specific situations. As a consequence, if the substantive interpretation is corrected, self–peer agreement should be higher than self–stranger agreement. Similarly, task-specific tests (e.g., figural and verbal) may represent the best way to measure maximum creative performance in specific tasks. But why do individuals differ in their perceived creativity and creative test performance?

A Behavioral Genetic Perspective

Since Galton's (1869) influential book *Hereditary Genius*, in which he claimed that genius runs in families, the possibility of creativity being heritable has been discussed. The genetic basis of creativity has been primarily examined by twin studies, which have used diverse tests and assessments of creativity. Classical twin studies allow an estimation of heritability (i.e., the degree to which individual differences are due to genetic differences), as well as estimations of the contributions of environmental influences that act to increase twins' similarity (i.e., shared environmental influences) and environmental influences that act to decrease twins' similarity (i.e., nonshared environmental influences).[1]

Behavioral genetic studies on creativity are scarce. In an early review, Nichols (1978) summarized 10 small twin studies that assessed creativity using tests and calculated mean intraclass correlations (ICCs) of .61 for monozygotic (MZ) twins and .50 for dizygotic (DZ) twins. Based on these measures, a moderate heritability of 22% was estimated, whereas 39% of the variance could be attributed to shared environmental influences, and the remaining 39% to nonshared environmental effects, including error of measurement. More recent studies replicated this finding of a moderate heritability of creativity (e.g., Grigorenko, LaBuda, & Carter, 1992), albeit the heritability tended to be larger for measures of perceived creativity, with less evidence of shared environmental contributions (e.g., Bouchard, Lykken, Tellegen, Blacker, & Waller, 1993). The findings on strong environmental contributions to individual differences in creative behavior and performance are in line with several perspectives that propose the environment as the primary source fostering creativity (e.g., Amabile, 1988; Simonton, 2003a; Sternberg & Lubart, 1996).

According to Simonton (2008), creativity should be considered as an interactive or emergent configuration of numerous polygenic characteristics. That is, the heritability of creativity as a heterogeneous phenomenon should be influenced by multiple, more rudimentary, partly heritable characteristics, such as intelligence, openness, and extraversion. This explains why creativity is associated with multiple characteristics, but none of them has been found to be sufficient to explain creativity. From this point of view, it would be fruitful to investigate various partly heritable characteristics as multiple determinants of the heritability of creativity.

Openness, extraversion, and intelligence have been found to be substantially heritable across multiple methods of measurement (Borkenau, Riemann, Angleitner, & Spinath, 2001; Deary, Penke, & Johnson, 2010; Kandler, Riemann, Spinath, & Angleitner, 2010; Plomin & Spinath, 2004). Both are affected by a large number of genetic variants (Davies et al., 2011; Verweij et al., 2012; Vinkhuyzen et al., 2012). Openness, extraversion, and intelligence may reflect essential genetically anchored core characteristics that may account for the heritability of creativity (Kandler, Zimmermann, & McAdams, 2014; Simonton, 2014). In addition, the heritability of creativity seems to be smaller. This might be due to a larger measurement error component or the fact that a large component of individual differences in creativity should be accounted for by environmental factors (Amabile, 1988; Sternberg & Lubart, 1992).

Aims of the Present Study

The current study aimed to investigate different aspects of creativity and the contributions of possible predictors. According to the mentioned (metrological or substantive) dualism, we hypothesized two aspects of creativity, resulting in a two-dimensional structure of creativity (Hypothesis 1). One dimension should reflect creativity as perceived creativity, capturing individual differences in typical creative thinking and behavior without reference to test performance. Typical behavior can be measured with self-reports and is well observable by well-informed others, such as peers. The other dimension should reflect individual differences in creative test performance, which should be best measured with tests.

As indicated by some previous studies (e.g., Batey et al., 2010; Furnham et al., 2008), we expected perceived creativity to be associated primarily with openness and extraversion, whereas creative test performance should primarily show links to intelligence (Hypothesis 2). Previous research indicated stronger or more robust links of creativity with openness, intelligence, and extraversion, whereas it provided rather inconsistent links to other personality traits (e.g., neuroticism, agreeableness, and conscientiousness). Our multitrait multimethod (MTMM) analysis allows for a validation of the hypothesized correlations across multiple measurement methods of creativity, personality traits, and intelligence (i.e., self-reports, peer reports, observer ratings, and tests).

The aim was not only to examine the structure of creativity and its correlates but also to gain a better insight into the underlying genetic and environmental sources of individual differences in creativity. Because of the outlined importance of the environmental context fostering creativity, we expected lower heritability estimates for creativity than for core personality traits and core cognitive abilities (Hypothesis 3). One reason for the lower heritability of creativity compared with personality traits and intelligence might be systematic differences in the reliability and validity of the measures (W. Johnson, Penke, & Spinath, 2011). Creativity is notorious for being difficult to assess psychometrically, and measurement error ends up as nonshared environmental variance in the classical twin design, thereby attenuating heritability estimates. Therefore, we used a latent phenotype modeling to control for systematic method and random error variance (Riemann, Angleitner, & Strelau, 1997). Thus, our study provided a more critical analysis of the often-hypothesized important role of the environmental context contributing to individual differences in creativity.

[1] These estimates are based (a) on the fact that identical or monozygotic (MZ) twins share 100% of their genes, whereas dizygotic (DZ) twins share on average only 50% of their genes that vary among humans; and (b) on the general assumption that both MZ and DZ twin pairs experience environmental effects that act to increase twins' resemblance to a similar degree. As a consequence, the larger the difference between the MZ twin and DZ twin intraclass correlation (ICC), the larger the heritability estimation (i.e., 2 times the difference: $h^2 = 2 \times [\mathrm{ICC}_{MZ} - \mathrm{ICC}_{DZ}]$); and the lower the difference, the larger the estimation of shared environmental influences ($c^2 = 2 \times \mathrm{ICC}_{DZ} - \mathrm{ICC}_{MZ}$). Finally, individual life experiences may act to decrease the similarity of twins, that is, the lower the MZ twins' similarity, the larger the contribution of individual environmental influences not shared by twins ($e^2 = 1 - \mathrm{ICC}_{MZ}$). In sum, classical twin studies allow splitting the variance into three additive components. This simple design ignores interactions and other forms of interplay between the three components.

Finally, we tested whether genetic variance in multiple measures of intelligence, openness, and extraversion can account for the genetic variance in creativity. According to the consideration of creativity as an outcome of a configuration of numerous polygenic characteristics (Simonton, 2008, 2014), we hypothesized that the vast majority of the genetic variance in creativity can be explained by the genetic variance in intelligence and personality traits (Hypothesis 4). The results have important implications for creativity as a psychological construct within the broad spectrum of personality-relevant individual characteristics.

Method

Participants

The current study was based on two partially overlapping twin data sets recruited from all over Germany through newspaper and media announcements as well as twin clubs: the German Observational Study of Adult Twins (GOSAT; Spinath, Angleitner, Borkenau, Riemann, & Wolf, 2002; Spinath et al., 1999) and the Bielefeld Longitudinal Study of Adult Twins (BiLSAT; Kandler et al., 2013). The GOSAT sample was collected between 1995 and 1997. It consists of 600 individuals (468 females and 132 males), including 168 MZ and 132 same-sex DZ twin pairs. Twins' ages ranged from 18 to 70 years ($M = 34.3$, $SD = 13.0$). Comprehensive descriptions of the sample and recruitment are detailed in Spinath et al. (1999, 2002).

All twin pairs who participated in the GOSAT also participated in the first (1993 to 1996; 732 MZ and 386 same- and opposite-sex DZ twin pairs) and second waves of the BiLSAT (1994 to 1997; 531 MZ and 275 DZ twin pairs), but only about 48% of the GOSAT sample participated in the third wave of the BiLSAT. Only in the BiLSAT's third wave (1999 to 2002), participants completed a test of figural creativity. This sample consisted of 844 individuals (684 females and 160 males), including 225 MZ and 113 DZ twin pairs as well as 168 unmatched twins. Age ranged between 22 and 75 years ($M = 39.1$, $SD = 12.6$). Comprehensive sample information and details about the recruitment procedure are reported in Kandler et al. (2013).

Although the samples cannot be considered representative with regard to zygosity and sex, they were heterogeneous with regard to education and occupational status. Because different measurement methods were used to capture creativity, cognitive abilities, and personality traits in each study, the overlapping sample was used to analyze the structure of creativity and its associations with cognitive abilities and personality traits based on latent phenotype modeling. This sample included 288 individuals (230 females and 58 males). Because of insufficient statistical power in the overlapping sample for genetically informative twin model analyses, the complete data of the GOSAT and BiLSAT were used separately to analyze the genetic and environmental sources of creativity and its specific aspects.

Measures of Creativity

Self-reports. In the second wave of the BiLSAT, participants provided self-ratings on 100 unipolar (UNIPOL) and 119 bipolar (BIPOL) adjective scales (Ostendorf, 1990). One adjective of the UNIPOL list was "creative." Participants were asked how well this adjective described him- or herself on a 5-point Likert scale (ranging from 0 = *not at all fitting* to 4 = *very fitting*; $M = 2.60$, $SD = 0.98$). The BIPOL list includes a bipolar adjective pair—"uncreative vs. creative." Participants were asked to locate themselves on a 6-point Likert scale (ranging from 0 to 5; $M = 3.53$, $SD = 1.11$). These items showed substantial correlations ($r = .67$). Both items were summed resulting in one creativity score per individual ranging between 0 and 9 ($M = 6.13$, $SD = 1.91$).

Peer reports. The BIPOL list was also filled out by peers at the second wave of the BiLSAT. For all individuals, at least one peer rater, and for almost all individuals (>99%), two peer raters, provided ratings on the BIPOL adjective list (Ostendorf, 1990). The individual twins were asked to recruit two peers who should ideally know them but not their twin siblings very well. The peer-rater consensus was $r = .31$ ($p < .001$). The ratings were summed to one creativity peer report score per individual, ranging between 0 and 10 ($M = 7.35$, $SD = 1.77$). The interrater reliability across all *z*-standardized self- and peer ratings was $ICC_{2,4} = .73$.

Video-based observer ratings. In the GOSAT, each individual was videotaped separately in 15 primarily verbal test situations. These were (in chronological order): (a) introducing oneself; (b) arranging three photographs in a meaningful order and telling an interesting story about them; (c) telling a dramatic story to each of three pictures from the Thematic Apperception Test (Murray, 1943); (d) telling a joke; (e) persuading an "obstinate neighbor" to turn down her music after 11:00 p.m. in a telephone role play; (f) refusing a request for help by a friend who just had a car accident in a second telephone role play; (g) introducing oneself to a stranger (actually a confederate) after the confederate introduced herself; (h) recalling objects one has just seen in a waiting room; (i) solving a complex logical problem, while the confederate from Setting 7 solves the same problem with enormous speed; (j) introducing a different confederate to the experimenter; (k) inventing a definition for a neologism and providing arguments for why that definition would be appropriate; (l) rigging up a high and stable paper tower within 5 min, using only scissors, paper, and glue; (m) reading 14 newspaper headlines and their subtitles aloud; (n) describing multiple uses of a brick with pantomime only; and (o) singing a song of one's choice. Videotaped sequences of the situations ranged in duration from 1 to 12 min, which summed up to about 60 min per individual. Each individual was rated on the basis of these sequences by four independent judges per situation (i.e., $15 \times 4 = 60$ independent judges per twin) on 35 bipolar adjective scales using a 5-point Likert scale (ranging from -2 to 2). Different panels of judges were employed for twins from the same pair. One of the adjective pairs was "uncreative vs. creative." This item was selected for the current study. The aggregate score of the 60 creativity ratings per individual ranged between -0.87 and 0.91, $M = -.00$, $SD = 0.31$, and the cross-rater cross-sequence reliability was excellent ($ICC_{2,60} = .90$).

Test scores. In the third wave of the BiLSAT, participants completed the German version of the T-88 (Häcker, Schmidt, Schwenkmezger, & Utz, 1975). In its original form, this test is a test of figural creativity and was a subtest of the objective test battery by Cattell and Warburton (1967). It consists of 18 incomplete line drawings. The participants were instructed to complete and name the drawings in any way they like. According to Anastasi and Schaefer's (1971; Schaefer, 1970) scale format and scoring instructions developed for the very similar Franck Drawing

Completion Test (Franck & Rosen, 1949), each item response was rated (with item order randomized) by three independent raters (two female and one male) regarding originality (with 5-point Likert-type scale ranging from 0 = *very poor* to 4 = *very clever or unusual idea*) and elaboration (3-point Likert-type scale: 0 = *not identifiable or arbitrary*, 1 = *identifiable*, and 2 = *identifiable and detailed or decorated*). Rater instructions included definitions of originality (i.e., the ability to create innovative, new, seldom, and ideational but realistic products) and elaboration (i.e., the ability to create filed and appropriate products), detailed anchors for each scale point of both scales, information on rater biases, and notes emphasizing to evaluate form as well as content, and discriminate elaboration from drawing ability. Ratings were averaged across items and raters. The interrater reliability was $ICC_{3,3}$ = .92 for originality and $ICC_{3,3}$ = .90 for elaboration. The cross-rater cross-item reliability was α = .96 for originality scores (M = 1.26, SD = 0.39; range = 0.04 to 3.38) and α = .94 for elaboration scores (M = 0.94, SD = 0.25; range = 0.06 to 1.91).

Measures of Personality Traits

NEO Five-Factor Inventory (NEO-FFI). For all participants of the GOSAT and BiLSAT, self-reports and two peer reports based on the German version of the NEO-FFI (Borkenau & Ostendorf, 1993; Costa & McCrae, 1989) were available. The NEO-FFI assesses personality traits with 12 items each. The internal consistency ranged between α = .63 (openness self-reports) and α = .85 (neuroticism peer reports). The correlations between self-reports and mean peer reports were r = .55 for neuroticism, r = .61 for extraversion, r = .57 for openness, r = .49 for agreeableness, and r = .54 for conscientiousness.

NEO Personality Inventory (NEO-PI-R). All individuals who participated in the third wave of the BiLSAT additionally completed the German revised NEO-PI-R (Costa & McCrae, 1992; Ostendorf & Angleitner, 2004), which provides more detailed measures of personality traits (48 items each). Again, for all individuals, at least one peer report, and for almost all individuals (>98%), two peer reports, were available. The internal consistency ranged between α = .86 (agreeableness peer reports) and α = .92 (extraversion peer reports). The correlations between self-reports and mean peer reports were r = .54 for neuroticism, r = .61 for extraversion, r = .53 for openness, r = .48 for agreeableness, and r = .53 for conscientiousness.

Measures of Intelligence

Leistungsprüfsystem (LPS-K). In the GOSAT, the short form of the LPS (Sturm & Willmes, 1983) was applied. This test is a highly reliable German intelligence test developed to measure Thurstone's (1938) primary mental abilities. It consists of seven subtests measuring vocabulary (two tests), word fluency, orthographical skills, reasoning, and spatial abilities (two tests). Internal consistency ranged from α = .86 to α = .94. Neubauer, Spinath, Riemann, Borkenau, and Angleitner (2000) calculated a verbal intelligence factor score ($LPS\text{-}K_V$, primarily indicated by the first four test scores) and a nonverbal factor score ($LPS\text{-}K_{NV}$, primarily indicated by the other three test scores) from this LPS-K data on the basis of two extracted oblique dimensions (r = .41), resembling Cattell's (1963, 1987) crystallized and fluid intelligence.

Advanced Progressive Matrices (APMs). In addition to the LPS, Raven's (1958) APMs were given, with a 20-min time limit (see Neubauer et al., 2000, for more details). The APM scores (α = .90) correlated higher with the $LPS\text{-}K_{NV}$ (r = .60) than with the $LPS\text{-}K_V$ (r = .44).

Brainteasers. Participants in the third wave of the BiLSAT completed a short intelligence measure consisting of 13 brainteasers. This method was developed to measure intelligence via 5-min telephone calls. Each brainteaser consists of a question and three possible answers, of which only one is correct (e.g., "April is to March as Tuesday is to [a] Wednesday, [b] Friday, or [c] Monday?" or "Which number should follow: 1, 2, 0, 3, −1? [a] 5, [b] 4, [c] −3"). The individual "true = 1" versus "false = 0" values for the 13 items were aggregated to individual sum scores (α = .75). Based on the overlapping sample of the GOSAT and BiLSAT, the correlations with the $LPS\text{-}K_{NV}$, $LPS\text{-}K_V$, and APM scores were r = .55, r = .27, and r = .56, indicating support for the validity of the brainteasers as indicator of (primary fluid) intelligence.

Sex and Age Corrections

Potential age and sex differences were out of the scope of the present study, but they inflate variance and twin similarity resulting from their shared age and often-shared sex. Thus, all variables were corrected for linear and quadratic age effects, as well as gender differences, using a regression procedure (McGue & Bouchard, 1984). Standardized residual scores were used in the following analyses.

Statistical Analyses

All model analyses were completed using the structural equation modeling software package IBM SPSS AMOS (Arbuckle, 2009). We first ran confirmatory factor analyses to test the hypothesized two aspects of creativity based on five creativity scores (self-reports, averaged peer reports, aggregated video-based observer ratings, and the two T-88 test scores) from all individuals who participated in both the GOSAT and in the third wave of the BiLSAT. Then, we examined the hypothesized variable correlations between all measures of creativity and intelligence, as well as personality traits. For this purpose, we used an MTMM validation based on all available data. In addition, we ran latent variable model analyses based on the data from the overlapping sample.

The overlapping sample provided insufficient statistical power for genetically informative twin model analyses. Therefore, we separately analyzed the BiLSAT and GOSAT twin data to examine the underlying genetic and environmental sources of creativity.

Results

Structure of Creativity

Correlations of the five creativity scores for both Twin A and Twin B subsamples are presented in Table 1. In order to test the hypothesized two-dimensional structure of creativity, a confirmatory factor analysis was conducted (see Figure 1). Four different models were tested. The initial model included only one latent τ-congeneric creativity variable that explained the correlation pattern of all five creativity measures (Figure 1a). The second model

Table 1
Intercorrelations of Creativity Indicators

Creativity measures	Self-report	Peer report	Video-based rating	T-88 elaboration	T-88 originality
Self-report		.42** (841)	.22** (260)	.16** (383)	.19** (383)
Peer report	.44** (895)		.18** (259)	.25** (377)	.21** (377)
Video-based rating	.21** (264)	.28** (264)		.19** (150)	.21** (150)
T-88 elaboration	.19** (425)	.23** (422)	.28** (144)		.61** (401)
T-88 originality	.12* (425)	.13* (422)	.26** (144)	.62** (425)	

Note. Correlations are presented for both randomized Twin A (below the diagonal) and Twin B subsamples (above the diagonal) based on all available data using pairwise deletion procedures; the number of individuals are shown in parentheses.
* $p < .05$. ** $p < .01$.

(Figure 1b) included an additional τ-equivalent factor accounting for the specificity of tested figural creativity (or method specificity due to the T-88). The third model (Figure 1c) alternatively included an additional τ-equivalent factor accounting for the specificity of perceived creativity captured via self-reports and ratings by well-informed peers. The fourth model (Figure 1d) was our preferred general-creativity-plus-two-aspects model.

Model fitting results yielded a very poor fit for the unidimensional creativity model (see Table 2). The alternative models provided good model fits (i.e., root mean square error of approximation [RMSEA] < .05 and comparative fit index [CFI] > .95; Bentler, 1990; Steiger, 1990). As expected, the general-creativity-plus-two-aspects model showed the best fit, which was indicated by the highest CFI, the lowest RMSEA, and a nonsignificant chi square. Factor loadings are presented in Figure 2a.

We also tested a model with equal fit but with an alternative specification as a hierarchical model (see Figure 2b). In this model, video-based observer ratings were allowed to indicate both creativity aspects, because creative behavior was measured in situations in which both perceived creativity (e.g., creating an interesting story) and creative test performance (e.g., solving a complex problem) affect the behavior. Thus, one latent τ-congeneric variable could be interpreted as perceived creativity, whereas the other represented (primarily figural) creative test performance. The two resulting latent creativity factors were allowed to be linked via a higher order general creativity factor.

Predictors of Creativity

Correlations between the five creativity scores and multiple measures of potential predictors (extraversion, openness, and intelligence) and suggested nonpredictors (neuroticism, agreeableness, and conscientiousness) are shown in Table 3. We found systematic cross-method cross-rater correlations across both randomized Twin A and Twin B subsamples between openness and all measures of creativity, whereas systematic correlations were found between extraversion and three measures of creativity: self-reports, peer reports, and video-based observer ratings. We did not find systematic correlations between creativity and neuroticism, agreeableness, or conscientiousness. Intelligence test scores were primarily associated with three measures of creativity: T-88 elaboration and originality scores (except LPS-K_{NV} and APM), and video-based ratings (except brainteasers).

We fitted a latent variable structure model with two correlated aspects of creativity, perceived creativity and tested figural creativity (cf. Figure 2b), and the MTMM validated correlates—openness, extraversion, and intelligence (cf. Table 3). This model analysis was based on the overlapping sample data. The broader and more reliable NEO-PI-R measures of openness and extraversion were used. The RMSEA indicated a good model fit and the CFI pointed to an at least acceptable fit (χ^2 = 149.98, degrees of freedom [*df*] = 57, RMSEA = .036, CFI = .937).[2]

The standardized regression weights and latent correlations are presented in Figure 3. The dotted paths between extraversion and tested figural creativity, as well as between intelligence and perceived creativity, reflect nonsignificant links. Fixing these paths to zero did not lead to a significant reduction in model fit ($\Delta\chi^2_{df=2}$ = 0.80, Δp = .67). In line with the proposed aspects of creativity, the two personality traits of extraversion and openness primarily predicted perceived creativity, whereas intelligence essentially predicted tested figural creativity. However, as already indicated in the MTMM correlation matrix (see Table 3), openness also represented a significant predictor of tested figural creativity. Therefore, we additionally tested whether openness accounted for the positive correlation between both aspects of creativity, which would indicate that openness may serve as a catalyst of general creativity or even as general creativity itself, as suggested by several researchers (e.g., McCrae, 1987). Fixing the residual correlation between perceived creativity and tested figural creativity to zero led to a significantly worse fit ($\Delta\chi^2_{df=1}$ = 19.07, Δp = .00), indicating that individual differences in openness to experience did not reflect variance in general creativity.

The MTMM correlation matrix also suggested that verbal intelligence (LPS-K_V) might reflect a more systematic predictor of tested figural creativity. Therefore, we modeled an additional direct path from LPS-K_V to latent figural creativity. This led to a significant improvement in model fit ($\Delta\chi^2_{df=1}$ = 14.97, Δp = .00) and a reduced effect from latent intelligence on tested creativity to β = .15 ($p < .05$). The direct effect from LPS-K_V was β = .30 ($p < .001$; see Appendix).

[2] A more complex model allowing for a self-report method factor ($\Delta\chi^2_{df=3}$ = 48.06; Δp = .00; RMSEA = .032; CFI = .952) increased the model fit but did not markedly change the estimates of path coefficients between latent variable scores.

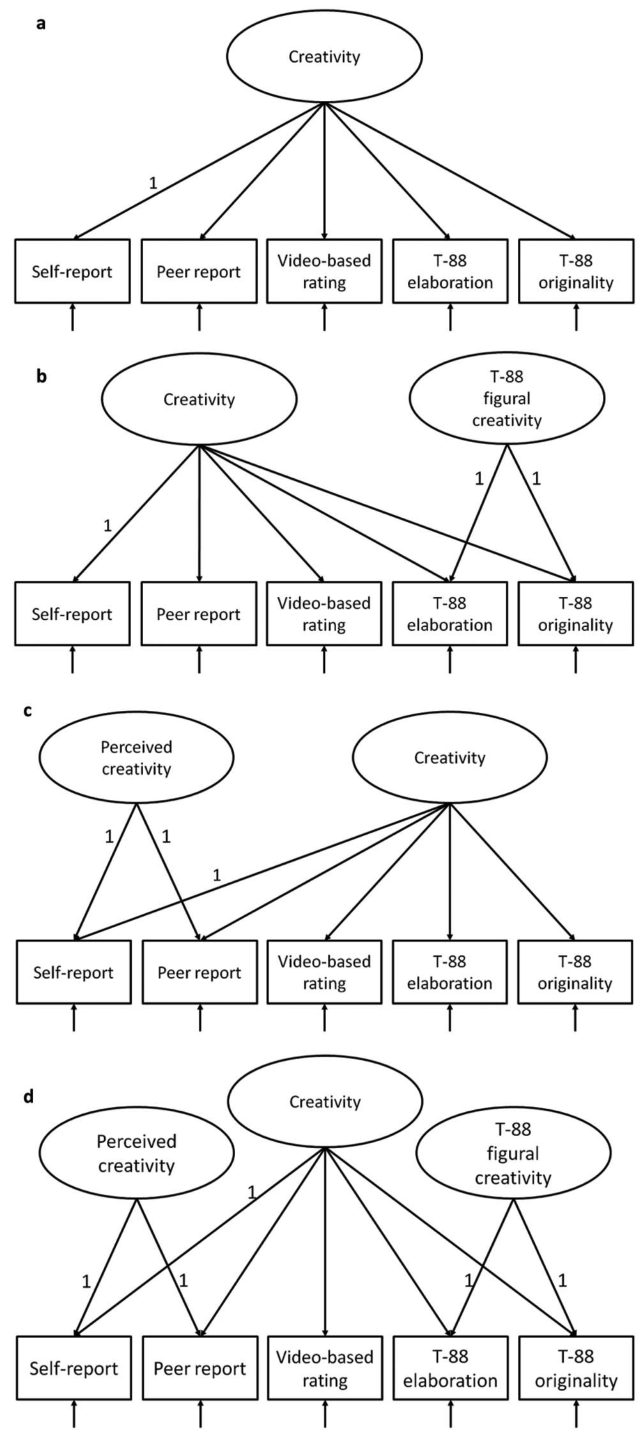

Figure 1. Different models for confirmatory factor analyses: (a) unidimensional creativity; (b) general creativity + tested figural creativity; (c) general creativity + perceived creativity; and (d) general creativity + tested figural creativity + perceived creativity.

Genetic and Environmental Sources of Variance in Creativity

Another aim of the study was to examine the genetic and environmental sources of individual differences in different aspects of creativity, and the role of openness, extraversion, and intelligence as a configuration of polygenic characteristics accounting for vast majority of the genetic variance in creativity. Because of too-low statistical power of the overlapping sample between the GOSAT and BiLSAT, we did separate twin model analyses for each data set.

Univariate quantitative genetic analyses. Our genetically informative (or environmentally sensitive) analyses were based on the classical design of twins reared together. This methodology allows a decomposition of the variance in a phenotype into a genetic component reflecting the effects of multiple genes that vary among humans (i.e., narrow-sense heritability, h^2), and two environmental components due to shared environmental influences common to both members of a twin pair (c^2) and nonshared environmental effects unique to each individual (e^2). The genetic effects are assumed to be completely shared by MZ twins and, on average, 50% are shared by DZ twins. Shared environmental influences on the variance reflect environmental circumstances that act to make twins similar, whereas nonshared environmental effects act to make twins dissimilar. This model assumes that MZ twins share environmental influences to the same degree as DZ twins do. It also assumes the absence of assortative mating, gene–environment correlation, and gene–environment interaction, which cannot be estimated with the classical twin design (see Neale, 2009, for more details). Because the nonshared environmental component is modeled as a residual component, it also includes variance attributable to random measurement error. Therefore, we ran latent phenotype models (see Riemann et al., 1997, or Nelling, Kandler, & Riemann, 2015) for all attributes of interest if more than one indicator was available, in order to control for the error variance component (see Figure 4).

Univariate model-fitting results based on MZ and DZ twin variance–covariance matrices are shown in Table 4. Individual differences in perceived creativity captured by self-reports, peer reports, and video-based observer ratings were partly due to genetic influences (33%, 27%, and 36%), whereas the heritability of tested figural creativity based on elaboration and originality test scores was rather low (5% to 8%) and not statistically significant. However, the heritability estimate (corrected for attenuation due to

Table 2
Confirmatory Factor Analyses: Model Fit Statistics

Model	χ^2	*df*	*p*	RMSEA	CFI
Unidimensional trait model	256.94	5	.00	.139	.698
General trait + TFC creativity	12.86	4	.01	.029	.989
General trait + PC creativity	20.46	4	.00	.040	.980
General trait + TFC + PC creativity	4.01	3	.26	.011	.999
Alternative hierarchical trait model	4.01	3	.26	.011	.999

Note. $N = 288$. TFC = T-88 figural creativity; PC = perceived creativity; *df* = degrees of freedom; RMSEA = root mean square error of approximation; CFI = comparative fit index.

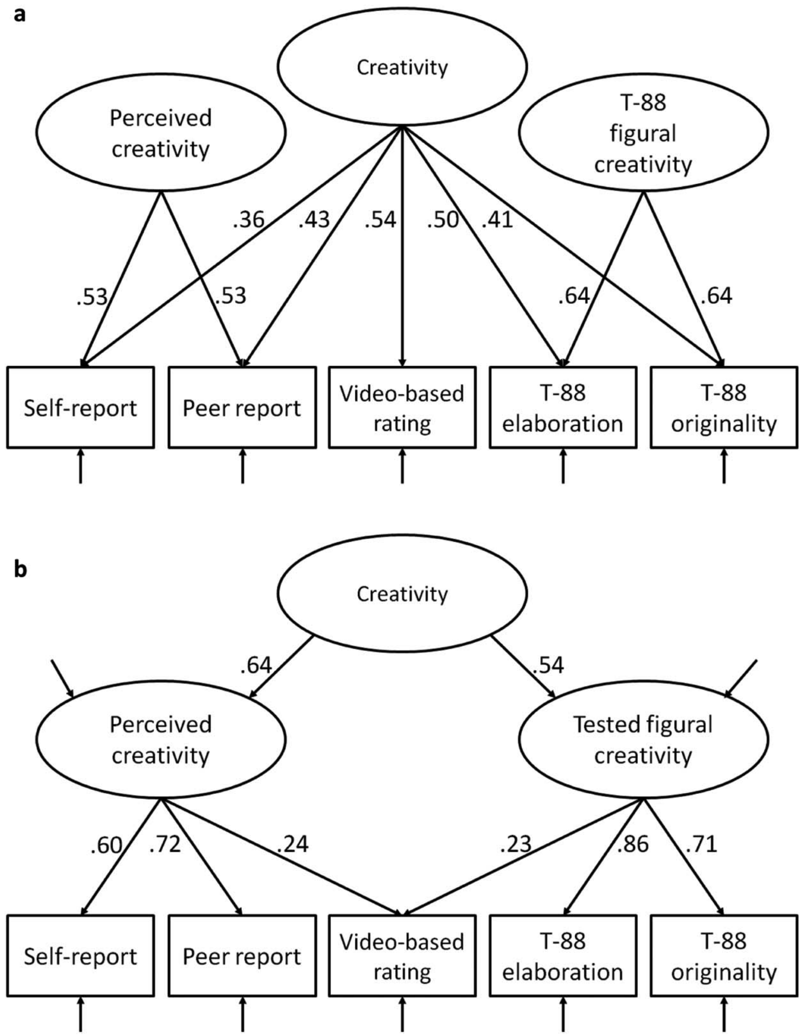

Figure 2. Estimations of factor loadings based on the best-fitting models shown in Table 2: (a) general creativity + tested figural creativity + perceived creativity, and (b) hierarchical creativity.

unreliability) of perceived creativity and tested figural creativity were 62% and 26%.

Whereas environmental influences shared by twins were negligible in the case of everyday creativity, shared environmental factors significantly contributed to individual differences in video-based ratings on creativity and tested figural creativity (20% to 42%). The primary environmental source of individual differences in creativity reflected environmental factors not shared by twins (38% to 70%).

The environmental variance in personality traits and intelligence was primarily attributable to influences not shared by twins contributing to twins' dissimilarity, whereas genetic factors primarily contributed to twins' resemblance. These findings are in line with previous behavior genetic research on core cognitive abilities and personality traits (A. M. Johnson, Vernon, & Feiler, 2008; Plomin & Spinath, 2004).

In line with our expectations, the heritability estimate for latent figural creativity scores (95% CI [.06, .45]) tended to be lower than those for latent extraversion (NEO-FFI, 95% CI [.52, .79]; NEO-PI-R, 95% CI [.33, .81]), openness (NEO-FFI, 95% CI [.51, .77]; NEO-PI-R, 95% CI [.39, .92]), and general intelligence (95% CI [.73, 1.00]). However, the heritability estimate for perceived creativity corrected for attenuation (95% CI [.40, .74]) was comparable with the estimates for personality traits.

Multivariate quantitative genetic analyses. Finally, we tested whether genetic variance in openness, extraversion, and intelligence can account for the genetic variance in creativity. For that purpose, we ran multivariate genetically informative regression analyses (see Figure 5). These models provide two kinds of information. First, they allow for an estimation of the degree to which individual differences in creativity measures are due to potential predicting variables. Second, they inform about genetic and environmental influences on the residual variance in creativity scores. Thus, with these models, it is possible to test whether the genetic variance in creativity is fully accounted for by the genetic variance in potential predictor variables by fixing the path $h = 0$ and comparing the model fit of this reduced model with the fit of the full model.

Table 3
Multitrait Multimethod Correlations Between Creativity and Potential Predictors

Potential predictors	Self-report (n = 263–885) A	Self-report B	Peer report (n = 263–879) A	Peer report B	Video-based rating (n = 148–290) A	Video-based rating B	T-88 elaboration (n = 143–425) A	T-88 elaboration B	T-88 originality (n = 143–425) A	T-88 originality B
Neuroticism										
Self-report$_{\text{NEO-FFI.1}}$	**−.16****	**−.16****	−.09*	−.08*	−.09	−.02	−.00	.08	−.01	.08
Peer report$_{\text{NEO-FFI.1}}$	**−.08***	**−.12****	−.07	−.09*	−.14*	−.14*	.01	.00	.03	−.04
Self-report$_{\text{NEO-PI-R.3}}$	−.13**	−.10	−.10*	−.06	.02	−.04	.05	.11*	.07	.04
Peer report$_{\text{NEO-PI-R.3}}$	−.10	−.03	−.12*	−.11*	−.07	.01	−.02	.02	.03	−.01
Extraversion										
Self-report$_{\text{NEO-FFI.1}}$	**.26****	**.24****	**.19****	**.14****	**.24****	**.26****	.00	.03	.02	.05
Peer report$_{\text{NEO-FFI.1}}$	**.17****	**.15****	**.19****	**.14****	**.29****	**.20****	.06	.02	.08	.08
Self-report$_{\text{NEO-PI-R.3}}$	**.18****	**.23****	**.15****	**.17****	**.23****	**.28****	−.01	.02	.04	.09
Peer report$_{\text{NEO-PI-R.3}}$	**.16****	**.13***	**.18****	**.14****	**.24****	**.16***	.00	.07	.04	.05
Openness										
Self-report$_{\text{NEO-FFI.1}}$	**.25****	**.26****	**.16****	**.20****	**.27****	**.35****	**.13****	**.16****	**.22****	**.18****
Peer report$_{\text{NEO-FFI.1}}$	**.15****	**.20****	**.24****	**.26****	**.32****	**.33****	**.12***	**.13****	**.13****	**.12***
Self-report$_{\text{NEO-PI-R.3}}$	**.27****	**.31****	**.19****	**.30****	**.28****	**.40****	**.21****	**.21****	**.29****	**.26****
Peer report$_{\text{NEO-PI-R.3}}$	**.12***	**.25****	**.22****	**.21****	**.45****	**.33****	**.22****	**.25****	**.23****	**.23****
Agreeableness										
Self-report$_{\text{NEO-FFI.1}}$	.05	.03	**.13****	**.08***	.06	.07	−.07	−.03	−.07	−.04
Peer report$_{\text{NEO-FFI.1}}$	.02	.04	**.13****	**.14****	.13*	.07	.10*	−.02	.07	.07
Self-report$_{\text{NEO-PI-R.3}}$	.08	−.03	.09	.05	−.04	.19**	−.11*	−.07	−.15**	−.07
Peer report$_{\text{NEO-PI-R.3}}$	.02	−.03	.12*	.09	.12	.04	−.03	.07	−.05	.07
Conscientiousness										
Self-report$_{\text{NEO-FFI.1}}$	.09**	.11**	.03	.03	−.05	−.13*	−.14**	−.14**	−.09	−.11*
Peer report$_{\text{NEO-FFI.1}}$	.02	.01	.10**	.05	.07	−.04	−.06	−.06	−.06	−.00
Self-report$_{\text{NEO-PI-R.3}}$	.12**	.02	.03	−.00	−.09	−.11	−.04	−.11*	−.08	−.05
Peer report$_{\text{NEO-PI-R.3}}$	.06	−.06	.06	.02	.07	−.03	.01	−.11*	−.04	−.08
Intelligence										
LPS-K$_{\text{NV}}$	−.05	.14*	.13*	.04	**.23****	**.27****	**.32****	**.18****	.09	.05
LPS-K$_{\text{V}}$	−.04	.02	−.01	.01	**.32****	**.32****	**.23****	**.17***	**.21****	**.23****
APM	−.08	.10	.12	.02	**.17****	**.17****	**.27****	**.14***	.09	.10
Brainteasers	−.06	.02	.05	.04	.14	.03	**.22****	**.27****	**.10***	**.21****

Note. A = randomized Twin A subsample; B = randomized Twin B subsample; NEO-FFI.1 = measure based on NEO-FFI at Wave 1 of Bielefeld Longitudinal Study of Adult Twins (BiLSAT); NEO-PI-R.3 = measure based on NEO-PI-R at Wave 3 of BiLSAT; LPS-K$_{\text{NV}}$ = nonverbal intelligence based on LPS-K; LPS-K$_{\text{V}}$ = verbal intelligence based on LPS-K; APM = Raven's Advanced Progressive Matrices; values in boldface are consistently significant across Twin A and Twin B subsamples as well as methods of measurement.
* $p < .05$. ** $p < .01$.

To increase the statistical power for parameter estimations, the analyses were based on three partly different data sources (see Table 5): (a) openness and extraversion self- and peer reports (NEO-FFI), and creativity self- and peer reports, as well as latent perceived creativity scores using the twin data from the first and second wave of the BiLSAT; (b) openness and extraversion self- and peer reports (NEO-FFI), intelligence test scores (except brainteasers), and video-based observer rating scores on creativity using the GOSAT data; and (c) all intelligence scores from the GOSAT, openness self- and peer reports (NEO-PI-R), and creativity test scores (T-88), as well as latent tested figural creativity using the twin data from the third BiLSAT wave. To further increase the statistical power, the model estimates were based on the full-information maximum likelihood procedure implemented in AMOS.

All models provided good fits to the data (see Table 5; RMSEA $< .023$; CFI $> .982$). Significant regression weights for self- and peer reports of openness and extraversion, or for both verbal and nonverbal intelligence scores, indicated independent contributions to creativity measures. This was the case in particular for video-based observer ratings on creativity. Openness, extraversion, and intelligence scores accounted for 10% to 30% of individual differences in creativity scores.

Fixing the residual genetic component of self-, peer, and observer-rated creativity, as well as for latent perceived creativity, to zero did lead to significant reductions in model fit (see Table 5). That is, openness and extraversion did not mediate the entire genetic variance in perceived creativity. Fixing the residual genetic variance in creativity test scores to zero did not lead to significant reductions in model fit. That is, the vast majority of the genetic influences on individual differences in these creativity scores could be accounted for by the genetic variance in intelligence and openness.

Discussion

The aim of the present study was to examine the structure and the sources of individual differences in creativity. The results of our study provided support for a hierarchical structure of creativity with different aspects related to different predictors. The findings have important implications for the construct creativity as individ-

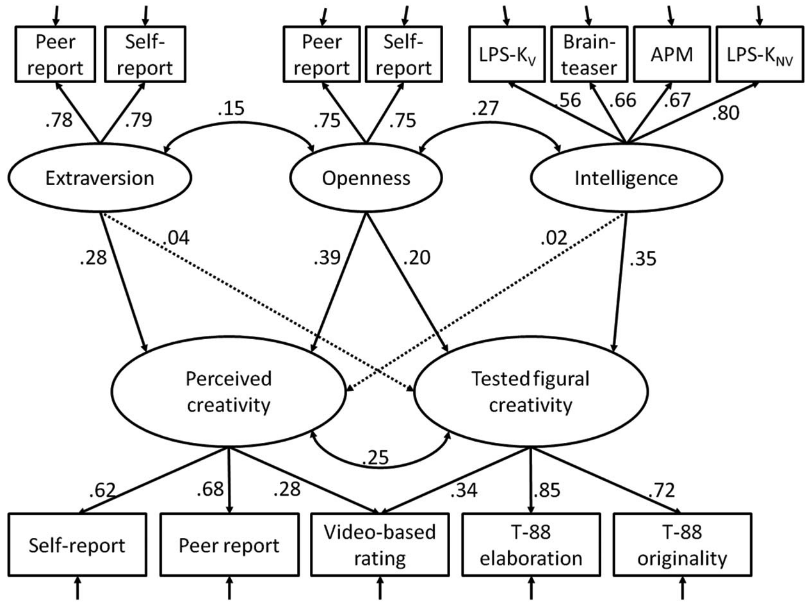

Figure 3. Estimations of latent variable structure modeling and links between creativity and its potential predictors (openness, extraversion, and intelligence) in regard to the two aspects of creativity (perceived creativity and tested figural creativity). Dotted paths represent nonsignificant links. LPS-K_{NV} = nonverbal intelligence based on LPS-K; LPS-K_V = verbal intelligence based on LPS-K; APM = Raven's Advanced Progressive Matrices.

ual characteristics, encompassing multimodal perspectives and multiple influences on creativity.

Two Aspects of Creativity

Concerning the structure of creativity, we hypothesized two aspects, which can be described as *perceived creativity* and *creative test performance* (Hypothesis 1). The results of our study support the two-dimensional structure. These two dimensions may represent metrological or substantive aspects or both.

One dimension may reflect a method artifact common with self-reports, peer reports, and video-based observer ratings due to the rating procedure to capture individuals' typical creative thinking and behavior. However, video-based observer ratings showed lower correlations with self- and peer reports than self-reports with peer ratings, indicating a substantive interpretation for this dimension in terms of perceived creativity leading to innovative products (e.g., paintings, designs, models, programs) that are useful at least for the productive creators themselves. Typical and everyday creative behavior can be measured more accurately with ratings by well-informed and familiar peers than with assessments by unfamiliar and external observers. This is in line with the finding of higher self–peer agreement compared with self–stranger or peer–stranger agreement regarding perceived creativity.

The other dimension may also mirror a method artifact, that is, use of the same measurement instrument (i.e., T-88), and (or) substance, that is, measuring ability-related aspects of creativity. Tested figural creativity showed positive links to creativity self-reports, peer reports, and video-based observer ratings. The associations with self- and peer reports may not be surprising, because figural creativity should also be well-perceivable in everyday creativity (e.g., painting, drawing, designing, tinkering, modeling, gardening, tailoring). However, the 15 videotaped test situations in the GOSAT include rather verbal tasks. The common aspect between the figural creativity test score and the latter was not the specific task, but the test situation itself.

Consequently, our study provided support for the hypothesis that general creativity encompasses different substantive psychological aspects. One aspect can be labeled as *typical or everyday creative thinking and behavior*, and the other as *creative test performance*, which can vary among different tasks, such as figural and verbal tasks.

The Roles of Personality Traits and Cognitive Abilities

The two aspects showed links to specific individual characteristics that have been proposed as requirements for being creative according to the investment theory of creativity (Sternberg, 2006). We expected perceived creativity to be primarily associated with openness and extraversion, whereas creative test performance should be mainly linked with cognitive abilities (Hypothesis 2). The findings of our study provided support for this hypothesis and indicate common and specific contributions of core personality traits and cognitive abilities to creativity.

Openness to experience appears to be a central characteristic, not only in the case of perceived creativity but also in the case of tested figural creativity. In fact, studies reported significant associations with rated as well as tested creativity (e.g., McCrae, 1987; Silvia et al., 2009). Increased openness to experience can be supportive in more than one way. First, active imagination and intellectual curiosity allow that more information can enter the focus of attention. Second, openness to new and unfamiliar expe-

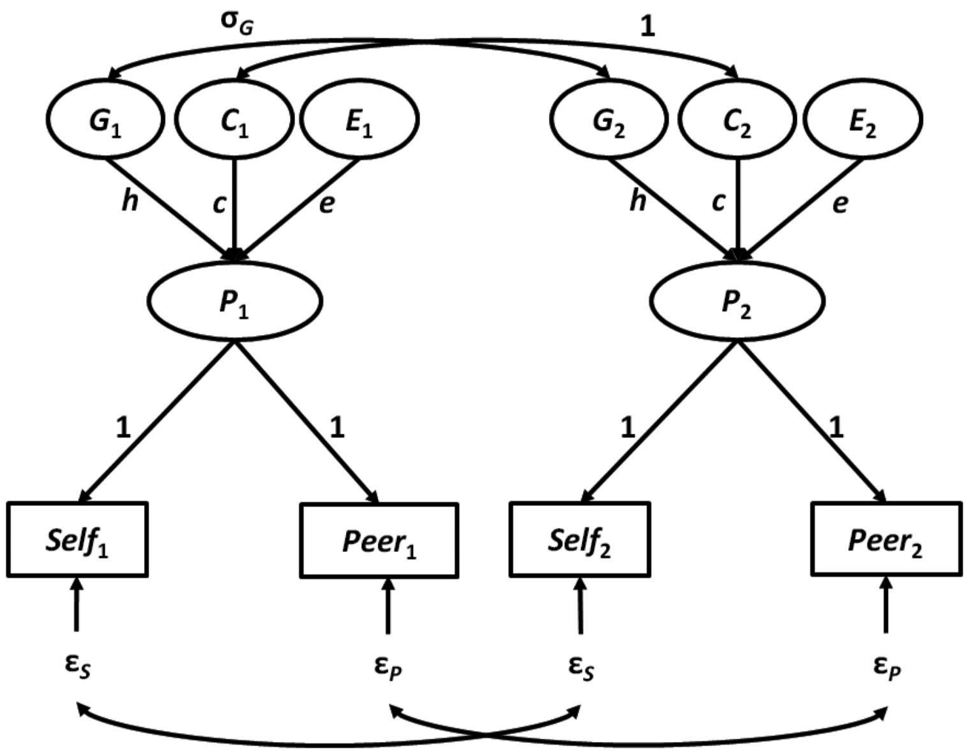

Figure 4. An example of a genetically informative twin model to decompose variance in latent phenotypes (*P*) of twins of a pair (Indices 1 and 2) into genetic (*G*) and shared environmental (*C*), as well as nonshared environmental (*E*), components. Path coefficients *h*, *c*, and *e* represent genetic and environmental effects; σ_G represents genetic twin covariance (standardized $\sigma_G = 1$ for monozygotic twins and $\sigma_G = 0.5$ for dizygotic twins); *Self* and *Peer* reflect self-reports and peer ratings; and ε_S and ε_P represent self-and peer-report-specific components including random error.

riences and objects may support an entering of unusual information into the creative combinatory process, including strange objects, unconventional patterns of thought, and independent opinion formation. Finally, high openness to new experience facilitates the enhancement of knowledge and expertise. In other words, high openness facilitates an integration of potentially conflicting or seemingly extraneous pieces of information in order to arrive at a relatively complex understanding of reality, which is essential for creative thinking and behavior. Thus, high openness appears to be fundamental and may serve as a catalyst for general creativity (McCrae, 1987). However, our study did not provide support for the idea that openness is identical to creativity or that both trait labels are interchangeable (e.g., J. A. Johnson, 1994), because openness did not account for the entire correlation between different measures of creativity and the entire genetic component in perceived creativity.

High nonverbal intelligence (often labeled fluid intelligence) additionally facilitates the extraction of more complex information from the environment, the faster combination of different information units, and a better evaluation of what is suitable (Cattell, 1963). Moreover, the findings provided support for the role of knowledge beyond general intelligence, in particular with respect to the originality of figural-creative aspects (i.e., T-88 originality scores) and verbal-creative test performances (i.e., during the videotaped rather verbal test situations). Our measure of verbal intelligence (often labeled *crystallized intelligence*) involves the availability of potentially relevant knowledge and the ability to use it. Knowledge is information that has been learned earlier and can thus be entered into the creative test performance.

The specific contribution of extraversion is somewhat less clear. This trait might help one to get into contact with many people who can inspire and foster one's own creativity, or support expressing one's own ideas in interaction with others. This may, in turn, facilitate and foster the development of innovative and useful ideas and products. Furthermore, creative ideas only become generally acknowledged as useful (i.e., creative achievements) when they are not kept back but are displayed or presented to others, which is facilitated by high extraversion. Notably, our creativity measures based on peer- and video-based ratings depend on the public display of creative ideas and behavior, suggesting a direct link to extraversion. Furthermore, studies have also shown that positive affectivity—a facet of extraversion—could facilitate the generation of ideational variation (e.g., Isen, Daubman, & Nowicki, 1987). Finally, the link between extraversion and creativity may be mediated by specific neurobiological pathways. Reduced cortical arousal or rather lower reactivity to sensory stimulation allowing for a simultaneous low-level activation of many different neuronal circuits have been associated with increased extraversion (Stelmack, 1990) and creativity (Martindale, 1989; see also Eysenck, 1995), but not with individual differences in openness and intel-

Table 4
Twin Correlations and Univariate Twin Model Results

Measures	Twin correlations		Model fit statistics					Standardized components		
	MZT	DZT	χ^2	*df*	*p*	RMSEA	CFI	h^2	c^2	e^2
Creativity										
BiLSAT second wave	*n* = 531	*n* = 275								
Self-report	.33**	.15*	1.04	3	.79	.00	1.00	.33**	.00	.67**
Peer report	.29**	.17**	2.37	3	.50	.00	1.00	.27**	.03	.70**
Latent phenotype PEC	.62**	.31**	12.25	11	.35	.01	1.00	.62**	.00	.38**
GOSAT	*n* = 168	*n* = 132								
Video-based rating	.57**	.38**	2.47	3	.48	.00	1.00	.36**	.20*	.44**
BiLSAT third wave	*n* = 222	*n* = 105								
Elaboration test (T-88)	.48**	.46**	3.97	3	.27	.02	.99	.05	.42**	.53**
Originality test (T-88)	.32**	.27**	9.26	3	.03	.05	.90	.08	.28*	.64**
Latent phenotype TFC	.50**	.37**	30.95	11	.00	.04	.96	.26*	.24*	.50**
Extraversion										
BiLSAT first wave	*n* = 732	*n* = 386								
Self-rep. (NEO-FFI)	.56**	.25**	1.87	3	.60	.00	1.00	.55**	.00	.45**
Peer rep. (NEO-FFI)	.40**	.19**	1.75	3	.63	.00	1.00	.40**	.00	.60**
Latent phenotype	.66**	.33**	12.57	11	.32	.01	1.00	.66**	.00	.34**
BiLSAT third wave	*n* = 225	*n* = 113								
Self-rep. (NEO-PI-R)	.50**	.37**	6.89	3	.08	.03	.95	.40**	.14†	.46**
Peer rep. (NEO-PI-R)	.42**	.28**	3.10	3	.38	.01	1.00	.35**	.08	.57**
Latent phenotype	.61**	.33**	16.63	11	.12	.02	.99	.57**	.04	.39**
Openness										
BiLSAT first wave:	*n* = 732	*n* = 386								
Self-rep. (NEO-FFI)	.55**	.32**	1.45	3	.69	.00	1.00	.44**	.11*	.45**
Peer rep. (NEO-FFI)	.49**	.30**	1.00	3	.80	.00	1.00	.37**	.12*	.51**
Latent phenotype	.78**	.46**	18.15	11	.08	.02	.99	.64**	.14*	.22**
BiLSAT third wave:	*n* = 225	*n* = 113								
Self-rep. (NEO-PI-R)	.52**	.28**	.11	3	.99	.00	1.00	.47**	.06	.47**
Peer rep. (NEO-PI-R)	.44**	.18	.82	3	.84	.00	1.00	.44**	.00	.56**
Latent phenotype	.74**	.41**	15.48	11	.16	.02	.99	.66**	.08	.26**
Intelligence										
GOSAT	*n* = 164	*n* = 129								
LPS-K_{NV}	.74**	.41**	.63	3	.89	.00	1.00	.61**	.12	.27**
LPS-K_{V}	.76**	.47**	5.31	3	.15	.03	.99	.58**	.18†	.24**
APM	.64**	.24**	6.79	3	.08	.03	.96	.62**	.00	.38**
Latent g	.93**	.46**	27.12	22	.21	.01	.99	.93**	.00	.07**
BiLSAT third wave	*n* = 209	*n* = 100								
Brainteasers	.41**	.33**	.35	3	.95	.00	1.00	.22*	.20*	.58**

Note. MZT = monozygotic twins; DZT = dizygotic twins; BiLSAT = Bielefeld Longitudinal Study of Adult Twins; GOSAT = German Observational Study of Adult Twins; PEC = perceived creativity based on self- and peer reports; TFC = tested figural creativity based on T-88 elaboration and originality test scores; h^2 = additive genetic component (i.e., narrow-sense heritability); c^2 = shared environmental component; e^2 = nonshared environmental component; LPS-K_{NV} = nonverbal intelligence based on LPS-K; LPS-K_V = verbal intelligence based on LPS-K; APM = Raven's Advanced Progressive Matrices; g = general intelligence; *df* = degrees of freedom; RMSEA = root mean square error of approximation; CFI = comparative fit index.
† $p < .10$. * $p < .05$. ** $p < .01$.

ligence. These alternative accounts for the supportive role of high extraversion for creativity are likely not mutually exclusive.

Environmental (Re)sources of Creativity

Beyond multiple individual characteristics, many researchers (e.g., Amabile, 1983; Sternberg, 2006) have highlighted the role of environmental factors as the most important source of individual creative thinking and behavior. In line with this notion, we expected to find moderate heritability estimates and a large contribution of environmental influences. In fact, heritability tends to be lower for creativity measures than for core personality traits and core cognitive abilities (confirming Hypothesis 3). After controlling for unreliability, however, the heritability of perceived creativity was comparable with the heritability of openness and extraversion (contradicting Hypothesis 3).

The relative influence of environmental factors on individual differences in tested figural creativity tended to be larger than the environmental component in everyday creativity. The finding implies that environmental factors contribute to individual differences in creativity and, in particular, in the case of creative test performance. Moreover, we found that environmental influences (even after controlling for error of measurement) primarily act to decrease the similarity of genetically identical twins, indicating that individual-specific environmental influences appear to play the most important role.

Previous experimental and field studies have found support for various specific environmental factors, such as autonomy of decision, positive contextual innovation climate, social support, reward, and the absence of social control or evaluative threat (e.g., Amabile, Goldfarb, & Brackfield, 1990; Byron & Khazanchi,

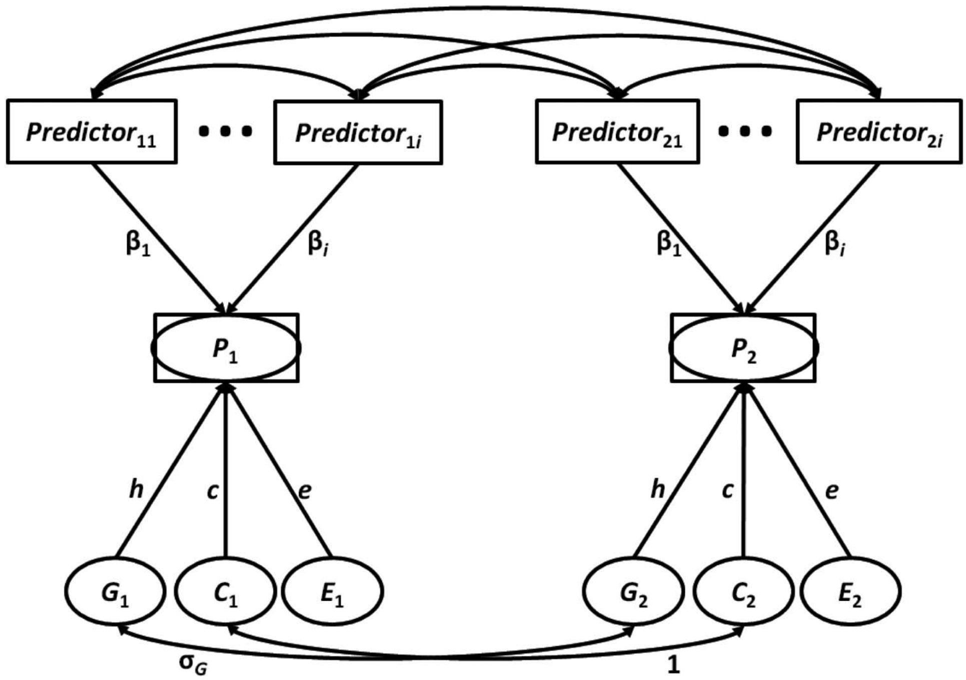

Figure 5. Multivariate quantitative genetic model to decompose residual variance in manifest (rectangle) and latent (circle) phenotypes (*P*) of twins of a pair (Indices 1 and 2) not accounted for by potential predictor variables into genetic (*G*) and shared environmental (*C*), as well as nonshared environmental (*E*), components: Path coefficients *h*, *c*, and *e* represent residual genetic and environmental effects; σ_G represents genetic twin covariance (standardized $\sigma_G = 1$ for monozygotic twins and $\sigma_G = 0.5$ for dizygotic twins).

2012; Eisenberger & Selbst, 1994; Isaksen & Kaufmann, 1990). Various studies have reported training effects on creativity, even though the findings have been rather inconsistent (e.g., Mansfield, Busse, & Krepelka, 1978; Rose & Lin, 1984). The effect of training may depend on the component of creativity and, thus, on the measurement of creativity (Scott, Leritz, & Mumford, 2004). Trainings may be more fruitful in the case of creative test performance. In any case, environmental factors may or may not force or enhance creativity, but at least they provide a fertile ground facilitating creative thinking and behavior (Hunter, Bedell, & Mumford, 2007; Weininger, 1977).

Genetic and Biological Sources of Creativity

Both environmental and genetic factors contribute to individual differences in creativity. Our multivariate behavioral genetic findings suggest that the genetic variance in tested figural creativity and a large amount of (rather verbally expressed) creativity captured via observer ratings on videotaped test situations can be explained by the genetic variance in intelligence, openness, and extraversion (confirming Hypothesis 4). However, the vast majority of the genetic variance in perceived creativity was not attributable to genetic influences on individual differences in openness and extraversion (contradicting Hypothesis 4). This may have different implications.

On the one hand, perceived creativity is a partly heritable trait, which reflects a valid personality construct and cannot easily be reduced to other personality traits. It may be genetically linked to other personality traits but may also reflect a distinct attribute within the personality system.

On the other hand, openness and extraversion are not the only traits contributing to creative thinking and behavior. The specific genetic variance in perceived creativity might be explained by other heritable characteristics. Sternberg and Lubart (1992) mentioned specific *thinking styles* and *intrinsic motivation* as additional important predictors of creativity. It seems reasonable to assume that people would not show a specific creative activity, such as producing a piece of art, without the interest in doing it. Artistic-creative interests are substantially heritable and, despite being substantially linked to openness to experience, only about one fourth of the genetic variance in artistic-creative interests is common with openness and other personality traits (Kandler et al., 2011).

Consistent with the consideration of creativity as a configuration of numerous polygenic characteristics, all potential predictors investigated in the current study—verbal and nonverbal intelligence, openness, and extraversion—showed common as well as specific contributions to individual differences in creativity. However, genes do not directly influence creative thinking and behavior. Most genes unfold their effects, over development and in interplay with environmental influences, in neuroanatomical structures and neurocognitive processes.

There is a growing and fruitful field of neuroscience of creativity, which offers potential pathways from genetic and environmental factors to individual differences in creativity.

Table 5
Multivariate Twin Model Results

Model results	BiLSAT 1st + 2nd wave: Self-report	BiLSAT 1st + 2nd wave: Peer report	BiLSAT 1st + 2nd wave: Latent PEC	GOSAT Video rating	GOSAT + BiLSAT 3rd wave: Elaboration test score	GOSAT + BiLSAT 3rd wave: Originality test score	GOSAT + BiLSAT 3rd wave: Latent TFC
Model fit statistics							
χ^2	43.15	25.62	112.90	58.77	51.51	68.89	159.12
df	31	31	71	52	45	45	101
p	.07	.74	.00	.24	.23	.01	.00
RMSEA	.019	.000	.023	.011	.011	.022	.022
CFI	.996	1.00	.988	.998	.996	.983	.969
Regressions (β)							
Extraversion self-rep.	.19**	.14**	.25**	.17**			
Extraversion peer rep.	−.01	.06†	.04	.12**			
Openness self-rep.	.19**	.05†	.19**	.15**	.10*	.20**	.11*
Openness peer rep.	.07*	.23**	.23**	.15**	.11**	.10*	.12*
LPS-K_{NV}				.18**	.08†	−.01	.08
LPS-K_{V}				.16**	.11*	.27**	.13*
APM				.01	−.03	−.01	−.03
Brainteasers					.11*	.08†	.12*
Explained variance + residual genetic, shared, and nonshared environmental components							
R^2	.10**	.10**	.22**	.29**	.10**	.15**	.12**
h^2	.26**	.24**	.47**	.15*	.02	.13	.15†
c^2	.00	.00	.00	.16*	.37**	.17†	.25*
e^2	.64**	.66**	.31**	.40**	.51**	.55**	.48**
Model test: $h^2 = 0$							
$\Delta\chi^2$	8.71	5.43	10.60	3.95	.01	.12	.75
Δdf	1	1	1	1	1	1	1
Δp	.00	.02	.00	.05	.92	.74	.39

Note. PEC = perceived creativity based on self- and peer reports; BiLSAT = Bielefeld Longitudinal Study of Adult Twins; GOSAT = German Observational Study of Adult Twins; TFC = tested figural creativity based on T-88 elaboration and originality test scores; *df* = degrees of freedom; RMSEA = root mean square error of approximation; CFI = comparative fit index; LPS-K_{NV} = nonverbal intelligence based on LPS-K; LPS-K_{V} = verbal intelligence based on LPS-K; APM = Raven's Advanced Progressive Matrices; R^2 = explained variance by potential predictors; h^2 = additive genetic component (i.e., narrow-sense heritability); c^2 = shared environmental component; e^2 = nonshared environmental component.
† $p < .10$. * $p < .05$. ** $p < .01$.

This research focuses on neuronal networks, such as interactions between executive and default mode networks (e.g., Beaty et al., 2014), or how both top-down and bottom-up processes yield innovative ideas (see Vartanian, Bristol, & Kaufman, 2013, for an overview). For example, facets of openness, such as openness to ideas, aesthetics, and liberal values, appear to be specifically associated with neuronal activity in dorsolateral regions of the prefrontal cortex (DeYoung, Peterson, & Higgins, 2005) and in the anterior cingulate cortex (Amodio, Jost, Master, & Yee, 2007). Both regions are parts of, or are connected with, the frontoparietal network, which is responsible for producing innovative ideas (Shamay-Tsoory, Adler, Aharon-Peretz, Perry, & Mayseless, 2011). Increased neuronal activity in the prefrontal cortex has also been found to be associated with improved intelligence test performance (Gray, Chabris, & Braver, 2003). Furthermore, more intelligent individuals show increased neuronal efficiency (Neubauer & Fink, 2005) and have more intact neuronal connections across the brain (Penke et al., 2012). That is, more-intelligent people often use fewer cortical areas but show more neuronal activity in used regions and better neuronal connections between them. This should facilitate useful selection and quicker integration of information to produce innovative ideas during test performance.

Strength, Limitations, and Outlook for Future Research

The present study extends previous research on the structure and sources of individual differences in creativity by using multiple measures and methods of measurement, as well as genetically informative and environmentally sensitive data, to investigate creativity, to disentangle its underlying genetic and environmental sources, and to examine the roles of core personality traits and intelligence. Yet several limitations have to be mentioned that should be addressed by future research.

First, our sample was relatively small and largely female, with an overrepresentation of MZ twins compared with DZ twin pairs. Future studies with larger data sets and balanced distributions of sexes should replicate the findings of our study and may focus on sex differences in the structure and sources of creativity.

Second, the different measures of creativity were partly captured at different measurement occasions. Although we have found similar patterns of correlations and sources within and across measurement occasions, to the degree creativity is liable to change over time, the links between variables are underestimated in our study relative to a design assessing all variables concurrently.

Third, our study focused on the additive contributions of potential predictors on creativity, as it relied on the additivity of genetic and environmental components. Interactions may occur between these sources, resulting in synergetic and compensatory influences. For example, very strong expertise in a field may help to compensate low openness and intelligence, or it might hinder creativity because of a closed and engrained perspective. In addition, increased genetically anchored tendencies to creativity may enhance the influence of the environment, such as openness to experience may facilitate the effects of trainings (Simonton, 2008) and extraversion may enhance the influence of the social network size (Kéri, 2011).

Finally, the current study focused on the contribution of environmental sources to individual differences in creativity and investigated the roles of core personality traits (i.e., openness and extraversion) and intelligence as partly heritable contributors to creativity. Sternberg (2006) also highlighted task-focused motivation and decisions about how to deploy the cognitive skills as important antecedents of creativity. Future studies should include these aspects and investigate their roles in the nature of creativity.

Conclusions

The aim of this genetically informative MTMM study was to provide a deeper understanding of the structure and sources of individual differences in creativity. Our study highlights creativity as broad psychological construct encompassing different aspects, such as perceived creativity and creative test performance. Cognitive abilities (verbal and nonverbal intelligence) and specific personality traits (openness to experience and extraversion) reflect important ingredients of creativity. Whereas openness reflects a primary predictor of general creativity, extraversion is specifically related to perceived creativity, and intelligence appears to contribute to creative test performance in specific tasks (e.g., figural and verbal tests). Core personality traits and cognitive abilities primarily mediate the genetic influences on individual differences in creativity. However, substantial environmental influences (beyond measurement error influences) are apparent and reflect facilitators or impediments of creative thinking and behavior, and, in particular, of creative test performance.

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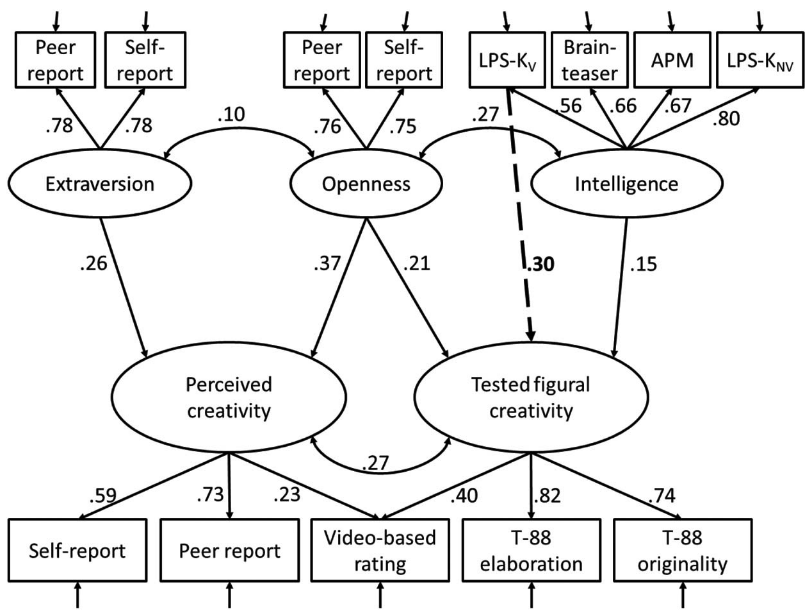
Appendix

Best Fitting Structure Model

This figure illustrates the best fitting structure model including estimations of latent variable structure modeling and links between creativity and its potential predictors (openness, extraversion, and intelligence) with regard to the two aspects of creativity (perceived creativity and tested figural creativity). The estimations are based on the best-fitting model allowing for an additional link between LPS-K_V and tested figural creativity (dashed path).



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