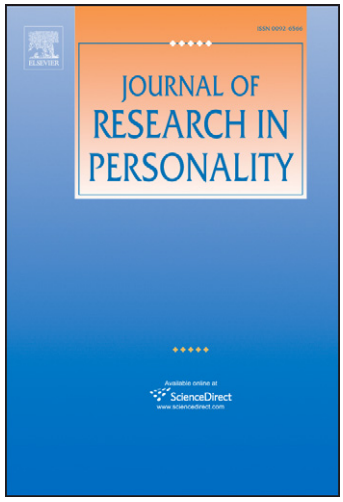

Openness, Fluid Intelligence, and Crystallized Intelligence: Toward an Integrative Model

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PII: S0092-6566(12)00003-7
DOI: 10.1016/j.jrp.2012.01.002
Reference: YJRPE 3167

To appear in: *Journal of Research in Personality*

Please cite this article as: Ziegler, M., Danay, E., Heene, M., Asendorpf, J., Bühner, M., Openness, Fluid Intelligence, and Crystallized Intelligence: Toward an Integrative Model, *Journal of Research in Personality* (2012), doi: 10.1016/j.jrp.2012.01.002

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Toward an Integrative Model

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Author Note

We are grateful for the input and the support from Teresa Schachtl, Natalia Zorkina, and Yuri Bassiakou.

Abstract

Many studies are concerned with the bivariate relationships between Openness, fluid intelligence (Gf), and crystallized intelligence (Gc). Results suggest an influence of Gf and Openness on Gc. However, the overlap between Gf and Openness is rarely controlled for. Moreover, interaction effects or longitudinal influences are also often neglected. The present two studies aimed to elucidate exactly these interactions and longitudinal influences. Besides a main effect of Gf on Gc, Study 1 (*N*=180) revealed an interaction effect between Openness and Gf. Study 2 utilized longitudinal data (*N*=173) and identified an effect of Openness on the development of Gf. Gf and Openness predicted Gc 6 years later. A model integrating the results and providing a theoretical framework and outlook is proposed.

Keywords: Intelligence; Openness to Experience; Fluid Intelligence; Crystallized Intelligence; Investment Theory; personality intelligence interface; Environmental Enrichment Hypothesis; process model; Environmental Success Hypothesis

Openness, Fluid Intelligence, and Crystallized Intelligence: Toward an Integrative Model

The interface between personality and intelligence has been the focus of several studies (Ackerman & Heggestad, 1997; Ashton, Lee, Vernon, & Jang, 2000; Harris, Vernon, & Jang, 2005; Ziegler, Knogler, & Bühner, 2009). In particular, the relationship between Openness to Experience and intelligence has been the focus of much research (Ackerman & Heggestad, 1997; DeYoung, Peterson, & Higgins, 2005). However, complex models integrating intelligence and personality and the way they interact with each other have been scarce (Ackerman, 1996; Chamorro-Premuzic & Furnham, 2004; Gow, 2005). A prominent exception to this is the intelligence-as-Process, Personality, Interests, and Intelligence-as-Knowledge (PPIK) model by Ackerman (1996) which includes ideas by Cattell (1943, 1987). The present studies were conducted in order to test some of the ideas brought forward hitherto and to add to this literature. To this end the relationship between fluid intelligence (Gf), crystallized intelligence (Gc), and Openness to experience was examined. Study 1 focused on possible interactions between Openness facets and Gf concurrently predicting Gc. In Study 2, data from the Munich Longitudinal Study on the Genesis of Individual Competencies (LOGIC, see Weinert & Schneider, 1999) were reanalyzed to explore the interplay between the constructs in a longitudinal setting.

Within the following passages the bivariate relationships between Gf, Gc, and Openness are shortly reviewed to lay the ground for the more complex models including all three traits.

Fluid Intelligence and Crystallized Intelligence

McGrew (2009) argued for the use of the well-established Cattell-Horn-Carroll model in intelligence research. He defined Gf as "the use of deliberate and controlled mental operations to solve novel problems that cannot be performed automatically" (p. 5) and Gc as "the knowledge

of the culture that is incorporated by individuals through a process of acculturation. Gc is typically described as a person's breadth and depth of acquired knowledge of the language, information and concepts of a specific culture" (p. 5). Based on these definitions as well as on other empirical findings (Ackerman, 1996; Ackerman & Rolfhus, 1999), the crystallized and fluid intelligence test scores used in the current studies can be seen as markers for these specific constructs.

A longstanding and very influential theory about the relationship between Gf and Gc is Cattell's Investment Theory (1943, 1987). According to this theory, Gf results in a faster and broader accumulation of Gc. Ackerman (1996) built on that theory in his PPIK model. He differentiated between intelligence-as-process and intelligence-as-knowledge. He wrote about intelligence-as-process that "… it seems clear that the speeded aspects of intelligence…are well-encompassed within a 'process' categorization. These information-processing components include Reasoning, Memory-Span (short-term, or working memory), Perceptual Speed, and Spatial Rotation…" (p. 239). The present research focused mainly on reasoning. Regarding intelligence-as-knowledge, Ackerman wrote: "The nature of intelligence-as-knowledge matches the first description of Gc provided by Cattell in his Investment Theory…" (p. 241). Furthermore, Ackerman suggested that intelligence-as-process has a causal influence on intelligence-as-knowledge such that more knowledge will be gathered if a person has higher fluid intelligence. Clearly, these construct definitions as well as the assumed Gf influence on Gc are in line with Cattell's Investment Theory. Empirical evidence supports this bivariate model has and shown moderate relationships between Gf and Gc (e.g., Ackerman, Bowen, Beier, & Kanfer, 2001; Bühner, Krumm, Ziegler, & Plücken, 2006; Rolfhus & Ackerman, 1999).

Openness and Crystallized Intelligence

Costa and McCrae (1992) reasoned that some of the adjectives used to measure Openness have an intellectual connotation, which led other researchers to call the factor Intellect (Saucier, 1994). A person open to experience is curious, imaginative, willing to deal with new themes, and eager to learn. Based on this simple description, it could be argued that such a person spends more time trying to figure out new problems or learning new things. Moreover, a person high in Openness to experience might be more likely to encounter new situations and receive new information. This could lead to more learning opportunities. The idea of specific personality traits positively influencing the development of cognitive abilities through providing more learning opportunities has already been suggested by Cattell (1987, p. 449). Even though Cattell did not use the term Openness (the Big 5 were suggested later), he included a general factor S_e as a variable influencing Gc. S_e consists of time invested into learning, interests, and memory. Surely, Openness goes hand in hand with more time spent on learning. Thus, it should not be surprising that Gc is positively influenced by Openness. Openness is also a vital part in Ackerman's PPIK model in which it is regarded as a major variable influencing the development of knowledge.

Exactly this influence of Openness on Gc has been investigated in an extensive study by Ashton et al. (2000). Those authors demonstrated that the Openness facet Understanding revealed the largest correlation with knowledge tests. According to Ashton et al., this is because "… many Understanding items describe preferences for artistic, literary, and scientific activities, and such interests would naturally be expected to correlate with the general knowledge that is assessed by the crystallized intelligence subtests" (p. 205). This argumentation is in line with the

reasoning stated above; that is, Openness to experience leads to learning opportunities, and thus increases Gc.

The importance of differentiating between different Openness facets when investigating the Openness-Gc relationship has been demonstrated also in a recent study by Zimprich, Allemand, and Dellenbach (2009). Those authors reported positive and moderate correlations between different Openness facets (Aesthetic Interests, Intellectual Interests, and Unconventionality) and Gc. Moreover, a suppressor effect was observed for Aesthetic Interests when Gf and Gc were regressed on the Openness facets. Based on the NEO model, DeYoung et al. (2005) investigated the relationship between Openness facets and Gc. They found that significant and small to moderate correlations emerged between Gc and the Openness facets Fantasy, Aesthetics, Ideas, and Values.

In sum, theoretical ideas regarding the influence of personality on the Gc have already been brought forward by Cattell and can also be found in Ackerman's PPIK model. Recent theoretical developments designated Openness to experience as an important individual difference variable influencing Gc. Empirical results have documented a substantial relationship between Openness and Gc. Additionally, literature has acknowledged the necessity of differentiating between Openness facets.

Openness and Fluid Intelligence

Theoretical models seldom include a link between Openness and Gf. Ackerman's PPIK model for example does not speak to this bivariate relationship. Oftentimes it is argued that the correlation between measures of Openness and Gf are too small to speak of a substantial relationship. Ackerman and Heggestad (1997) reported meta-analytical results that showed significant yet small correlations between Openness and so-called general intelligence. General

intelligence in this analysis encompassed two broad factors: intelligence-as-process and intelligence-as-knowledge. Thus, it can be interpreted as a blend of both Gf and Gc, and therefore allows for no clear conclusions regarding the relationship between Openness and Gf. Studies which employed measures that can more directly be regarded as Gf measures yielded more precise findings. Results from the LOGIC study showed that there was a moderate and significant correlation (r = .32) between Openness at ages 4 to 6 and Gf at age 9 (Asendorpf & Van Aken, 2003b). Moutafi, Furnham, and Crump (2003) reported that Openness to experience was a good predictor of Gf. Moreover, they identified Openness to Ideas as the facet with the strongest relationship to Gf. Other studies suggested small yet significant correlations, typically between .10 and .25 (e.g., Ackerman, Beier, Bowen, & Kanfer, 2001; Ashton, Lee, Vernon, & Jang, 2000). The robustness of these findings across different age groups has recently been reported (Soubelet & Salthouse, 2011; Zimprich et al., 2009). Once again, it seems relevant to highlight the importance of content when looking at the relationship between Openness and Gf. Whereas Ashton et al. administered Gf tasks which included only figural and numerical content in their study, the LOGIC project, which revealed a more substantial Openness-Gf relationship, used verbal Gf tests. The study by DeYoung et al. (2005) mentioned above also yielded small to moderate and significant correlations between Gf and the Openness facets Ideas and Values using a broad range of tests.

In sum, even though earlier theoretical models did not include a relationship between Openness and Gf, empirical studies have yielded substantial correlations between Openness and Gf. However, it seems important to investigate these relationships on the facet level. Consequently, in Study 1, we used different Openness facets.

Process Models

As mentioned above, besides looking at the bivariate relationships, Ackerman also formulated a complex model in which the interplay between Gf, Gc, and Openness is a crucial part. In this PPIK model, Ackerman (1996) considered the role of personality traits and interests in the accumulation of intelligence-as-knowledge. He argued that intelligence-as-knowledge contains specific knowledge structures (e.g., the physical or social sciences). A personality factor that Ackerman described as closely related to intelligence-as-knowledge was Openness to experience. He further stated that people open to experience have greater verbal crystallized abilities and knowledge in the fields of arts and humanities. In his model, he elaborated that Openness and interests interact and influence time and effort spent acquiring knowledge. It was pointed out above that Ackerman's PPIK model is in parts based on Cattell's theoretical ideas. Whereas Ackerman mostly focused on the longitudinal and thus developmental relationships between Openness, Gf, and Gc, Cattell (1987) also pointed out that personality and cognitive abilities might interact to influence immediate performance.

Developmental Perspective

The PPIK model cited above indicates that Gf has a positive influence on the development of Gc (Investment Theory). Extending this theoretical assumption, it was suggested that Gf and Openness might also influence each other longitudinally. For example, Asendorpf and van Aken (2003b) reported a longitudinal influence of Openness at ages 4 to 6 on Gf at age 9 (r = .32). In a study by Raine, Reynolds, Venables, and Mednick (2002), exploratory behavior (as an indicator of curiosity) was measured in a sample of N = 1,795 3-year-old children. The score was predictive of verbal (r = .20) and figural (r = .24) Gf as well as general intelligence at age 11 (r = .25). Raine et al. (2002) suggested that the idea of environmental enrichment can be used to explain this influence. The environmental enrichment explanation would be that

Openness leads to more exploration of the environment, engagement in social interactions, and thus to the experience of "… an enriched, stimulating, varied, and challenging environment" (Raine et al., 2002, p. 669). In that sense, children are more often confronted with different scenarios in which the rules are unknown and therefore have to be inferred. Therefore, Openness would foster Gf. We will call this mechanism the Environmental Enrichment Hypothesis. However, both analyses – the one by Asendorpf and van Aken as well as the one by Raine et al. – did not include a measure of Gf at the first measurement point. Thus, it is difficult to interpret the presumed causal relationships.

It would likewise be reasonable to assume that Gf fosters the development of Openness. This means that mastering new and unknown situations is more likely given a higher Gf score. This experience in turn should positively influence interest in new situations and thus the development and expansion of Openness (see DeYoung et al., 2005). Cattell (1987, p. 453) also hypothesized that an increase in certain personality traits is a result of constantly experiencing greater success because of higher intelligence. He names Autía (inner mental activity), a personality trait closely resembling Openness, as an example. We will call this hypothesis the Environmental Success Hypothesis. Consequently, within Study 2 we will look at the developmental relationships between Openness, Gf, and Gc in order to test the Environmental Enrichment and Success Hypothesis. Testing these hypotheses will potentially extend Ackerman's PPIK model.

To complete the picture, we will also include Gc into these analyses. If there actually are influences from Openness on the development of Gf or vice versa, it could also be possible that the constructs have an influence on the development of Gc via this indirect path. Thus, indirect longitudinal effects on Gc will be the focus of this paper as well.

Immediate Performance Perspective

The PPIK model focuses on the longitudinal development of knowledge. As mentioned before, Cattell was also concerned with interactions between Gf, Gc, and personality traits. In his 1987 book Cattell designated a whole chapter to the discussion of personality and ability interactions, also focusing on immediate performance. Such interaction effects on immediate performance between Gf and noncognitive constructs other than Openness have been reported before (Steinmayr, Ziegler, & Träuble, 2010; Ziegler et al., 2009). Ziegler et al. could show that achievement striving moderates the influence of Gf on school grades. However, on the topic of Openness as the personality domain most closely related to Gf, only a few studies looking at interaction effects can be found. Silvia and Sanders (2010) did not find any interaction between Gf and Openness when predicting interests. Unfortunately, their study did not include a measure of actual performance. Other studies mostly investigate the additive effects of Gf and Openness on Gc (Ziegler, Danay, Schölmerich, & Bühner, 2010; Zimprich et al., 2009). Despite the lacking studies, it seems reasonable to assume that those who are curious and enjoy intellectual engagement make stronger use of their fluid abilities. Thus, investigating possible moderating influences between Gf and Openness could not only improve predictions of Gc, it also has the potential to further our knowledge with regard to the mechanisms underlying the interface between Openness and Gf / Gc. Consequently, Study 1 focused on a possible interaction between Gf and Openness predicting Gc.

Summary and Outlook

Cattell and Ackerman both suggested models describing the interplay between Gf, Gc, and personality. Especially the personality trait Openness to experience has been the focus of recent empirical studies investigating the relationship between cognitive ability and personality.

Ackerman's PPIK model can be viewed as one of the first models integrating these traits. The present studies were conducted to test some of the assumptions of these models and to further extend our knowledge regarding the complex interplay between cognitive ability and personality. Prior research has demonstrated a strong relationship between Gf and Gc. It is assumed that fluid abilities foster crystallized intelligence (Investment Hypothesis). Moreover, longitudinal influences have been proposed for the development of Openness and Gf (Environmental Enrichment and Environmental Success Hypotheses). Prior research in this area is hard to interpret because clear causal relationships are difficult to infer. Findings regarding the relationship between these cognitive abilities on the one side and Openness on the other have shown significant and moderate correlations, especially when using specific Openness facets. The interplay between these traits during immediate performance has been discussed theoretically but rarely studied.

Study 1 aimed at illuminating possible interaction effects as suggested by Cattell. To this end the interaction between Openness and Gf in predicting Gc while differentiating between different Openness facets at the same time was investigated. Based on the findings by DeYoung et al. (2005), it was hypothesized that Openness to Fantasy, Aesthetics, Ideas, and Values would be associated with Gc but only the latter two with Gf. Study 2 aimed to investigate the longitudinal influence of Openness on Gf and vice versa while controlling for their initial relationship. It was hypothesized that Openness should foster the development of Gf and vice versa. Moreover, the direct and indirect contributions of each construct to Gc were analyzed. Thus, crucial parts of Ackerman's PPIK model as well as theoretical extensions will be tested.

Study 1

Method

Sample. The sample consisted of 180 (134 women) psychology students. The average age and semester were 24 (*SD* = 5.68) and 1.89 (*SD* = 2.01), respectively. All participants were native German speakers.

Test contents. The NEO-PI-R (Ostendorf & Angleitner, 2004) was used to measure Openness to experience and its facets. The questionnaire consists of 240 items assessing six facets for each of the factors of the Five Factor Model (i.e., Neuroticism, Extraversion, Openness to experience, Agreeableness, and Conscientiousness). Thus, each facet contains eight items. Participants are asked to rate themselves with respect to typical behaviors or reactions on a 5-point Likert scale, ranging from 1 (*strongly disagree*) to 5 (*strongly agree*). The internal consistency for Openness was α = .87. Facet reliabilities were α = .77 (Fantasy), α = .78 (Aesthetics), α = .81 (Feelings), α = .62 (Actions), α = .83 (Ideas), and α = .46 (Values).

In order to measure Gf, the basic module of the Intelligence Structure Test 2000 R (Amthauer, Brocke, Liepmann, & Beauducel, 2001) was used. This module consists of nine subtests with 20 items each. It can be described as a hierarchical model with verbal (Cronbach's α = .89), numerical (Cronbach's α = .96), and figural reasoning (Cronbach's α = .88) on the first level. Each reasoning facet consists of three subtests (Cronbach's α ranging from .55 to .88). On the next level, the reasoning types are combined to form one reasoning factor (Cronbach's α = .97) "… which would correspond to gf …" (Andre Beauducel, Brocke, & Liepmann, 2001, p. 981). In that sense, reasoning can be viewed as a good indicator of Gf. Thus, we will refer to this score as Gf from hereon. For an extensive description of the test, please see Bühner, Krumm, and Pick (2005).

As a measure of Gc, the Lexical Knowledge Test (Lexikon-Wissen Test, LEWITE, Wagner-Menghin, 1998) was used. The LEWITE is an adaptive test measuring vocabulary as

one marker of Gc. The person parameters are estimated from the Rasch model (Cronbach's α = .86). Participants have to complete sentences defining difficult words. They are provided with several alternatives from which they must choose the one that best completes the sentence. However, the words are so abstract that it is virtually impossible to deduce the correct solution from the given answers. A correct answer without guessing is possible only if a person knows the meaning of the word in advance. In this way, the test differs from the verbal reasoning sentence completion task from the IST 2000 R in which the correct answer must be deduced, and knowledge plays a minor role because the words used are known to most participants. Moreover, in a factor analysis using the Kaufmann-Assessment Battery for children, the LEWITE score loaded on the Gc factor and not on the Gf factor (Wagner-Menghin, 2004). Thus, evidence for its construct validity as a measure of Gc has been established.

Procedure. All tests were administered in a computer laboratory in groups of up to seven participants. The first task was to fill out the NEO-PI-R, followed by the IST 2000 R and the LEWITE. Participants received feedback on their test scores after completion.

Statistical procedure. In a preliminary analysis, the relationships between specific Openness facets and Gc as well as Gf were examined using SPSS 17.0. In a next step, a hierarchical regression analysis using structural equation modeling in MPlus 5.2 (Muthén & Muthén, 1998-2007) was used. In a first block, Gc was regressed on Gf and Openness. However, only those Openness facets that had a significant relationship with Gf, Gc, or both were used in order to avoid attenuation of possible interaction effects. Gf was specified with the nine subtests as indicators. Subtests using the same content also had correlated errors. In a second block, an interaction term was entered. We used a QLM approach as discussed in Marsh, Wen, and Hau (2004) and Klein and Moosbrugger (2000). Because incorporating a latent moderation term does

not yield a standardized solution, in order to obtain standardized results, all variables were *z*-standardized before conducting the latent regression analysis. Furthermore, latent variances were fixed at 1 to allow interpretation of relations within the structural model as standardized scores. In a last step, confidence bands and regions of significance for the moderation term were calculated (Preacher, Curran, & Bauer, 2006).

The assessment of global goodness-of-fit was based on the recommendations of Hu and Bentler (1999, p. 27). Thus, the Standardized Root Mean Square Residual ($SRMR \leq .09$), the Root Mean Squared Error of Approximation ($RMSEA \leq .06$), and the Comparative Fit Index ($CFI \approx .95$) were used. Beauducel and Wittmann (2005) warned that the usually suggested value of .95 for the CFI is often not achieved even given just small violations of simple structure. Because the tested model included two latent variables with more or less complex measurement models, a smaller value of the CFI (.90) was more appropriate (A. Beauducel & Wittmann, 2005, p. 71). Because modeling the latent moderation term does not allow computation of these indices, the sample-adjusted information criterion CAIC was also added to allow a comparison between the blocks.

Results

Correlational analysis. Table 1 contains means and standard deviations for all variables. Moreover, zero-order correlations are provided. It can be seen that Gc was significantly related to Gf. Significant relationships with Gf, Gc, or both occurred for the hypothesized Openness facets Fantasy, Action, Ideas, and Values. Consequently, the adopted model contained these facets as indicators for the latent Openness variable.

Regression analysis. In a first block, only the latent variables Openness and Gf were entered. Openness was modeled based on the facets Fantasy, Action, Ideas, and Values. All

loadings were significant ($p < .001$) and larger than $a = .44$. Gf had the nine subtests as indicators (all p's < .01 and all a's > .29). Model fit was: χ^2 (66) = 124.43, $p < .01$, SRMR = .086, RMSEA = .070 (90% CI: .051 - .089), CAIC = 6,738.42, CFI = .89. The CAIC for the model including the moderation term was 6,736.41, which indicates a slightly better model fit. The amount of explained variance in block 1 was $R^2 = .30$ ($p < .001$). However, only the regression weight for Gf was significant ($\beta = .45$, $p < .001$). Openness did not yield a significant main effect ($\beta = .14$, *ns*). Adding the interaction term explained another 3% of the variance of Gc ($\Delta R^2 = .03$, $p < .05$). The regression weight for Gf decreased ($\beta = .33$, $p < .05$). For Openness, a suppression effect occurred ($\beta = .23$, $p = .10$). The interaction term was significant ($\beta = -.17$, $p < .05$). To further explore possible interactions, confidence bands, regions of significance, and simple slope analyses were calculated (see Figure 1). As can be seen, the correlation between Openness and Gc decreased with an increase in Gf. The region of significance started with .21. This means, the correlation between Openness and Gc becomes insignificant for people whose Gf score is larger than $z = .20$. The confidence band for the moderating effect of Openness on the correlation between Gf and Gc mirrors the one just described. The region of significance was .61. As before, a dominance effect occurred[1]. This means, once a person scores above a certain value on one of the traits, the other does no longer impact Gc.

Study 1 Conclusions

Study 1 focused on the interplay between Openness, Gf, and Gc under an immediate performance perspective. It aimed to investigate possible interaction effects between Openness and Gf predicting Gc while paying attention to specific Openness facets. It could be shown that the Openness facets Fantasy, Ideas, Actions, and Values were related to cognitive abilities. This was expected and in line with prior findings by DeYoung et al. (2005). It can be assumed that

specifically these facets increase the probability that people are more willing to actively engage in situations that are new and challenging. Individuals scoring high on these facets describe themselves as analytical, interested, critical, progressive, tolerant, and interested in cognitive challenges. Thus, this group of people is interested not only in encountering new situations and topics, but also in analyzing and understanding them. Consequently, people with higher scores on these facets are more likely to acquire knowledge. The suppressor effect of Aesthetics found by Zimprich et al. (2009) could not be replicated as is often the case for suppressor effects. Especially the role of Openness to Values and Openness to Ideas is not surprising considering their substantial relationship to such concepts as need for cognition (NFC) or typical intellectual engagement (TIE; Fleischhauer et al., 2010; Wilhelm, Schulze, Schmiedek, & Süß, 2003). The idea that such more specific constructs are vital has already been acknowledged by Ackerman in his PPIK model. Generally, these findings underscore the importance of investigating such relationships at facet level.

Using these facets as indicators of Openness and controlling for Gf, no main effect of Openness on Gc could be found. Thus, the overlap between vocabulary as an indicator of Gc and Openness seems to be due to Gf. Many of the prior studies investigating the relationship between Openness and Gc did not control for Gf. However, based on the results of the moderation analyses, a different explanation is likely. The found dominance effect means that either of the traits loses its influence on Gc once the other trait surpasses a certain level. Considering that our sample scored about half a standard deviation above the norm (d = .53***), it is likely that this caused the lacking impact of Openness on Gc. Thus, future studies investigating this moderation should pay close attention to the levels of Openness and Gf within their sample.

Because content of the Gf tasks was controlled for in these analyses, it is unlikely that the strong influence of Gf found here is due to content overlap. Nevertheless, Gf had a strong influence on Gc in these data. Even after controlling for Openness, this effect remained intact. Clearly, this is in line with Cattell's Investment Theory and shows that Gf fosters the accumulation of Gc. However, it has to be mentioned here that Gf was not measured purely but using a reasoning score instead. This score might be contaminated with Gc variance artificially increasing the overlap with Gc.

There are some limiting aspects to this study, one of which is the criterion score. Even though vocabulary is an integrative part of Gc (McGrew, 2009), broader measures would be interesting and desirable in future research. Another limitation of Study 1 is the use of self-ratings for Openness. It could be argued that these self-ratings are nothing but confounded Gf. In that sense, people would refer to their actual ability when rating dispositions to discuss, probe, or otherwise work with intellectually challenging information. Finally, Study 1 could be criticized for using students as participants. Such a sample might yield restrictions in range [comparisons to the norm samples gave the following results: Gf: $F(670, 182) = 1.23$*; Gc: $F(272, 182) = 1.69$***; Openness: n.s], which in turn could affect the correlations. Considering the range restrictions for Gf and Gc, it could be concluded that the results represent a lower bound estimate of the effects discussed.

All in all, Study 1 demonstrated the assumed interaction between Openness and Gf on immediate performance (Gc). However, a dominance effect was found. Thus, the influence of Gf on Gc decreases with increasing Openness. Likewise, it was shown that the influence of Openness on Gc is dependent on the level of Gf.

Study 2

The goal of Study 2 was to test the longitudinal influences of Gf on Openness (Environmental Success Hypothesis) and vice versa (Environmental Enrichment Hypothesis). Moreover, the direct and indirect contributions of each construct predicting Gc were investigated while controlling for the other construct as well as the original overlap between them.

The data used to test these influences were originally gathered in the LOGIC project. Due to the longitudinal nature of the LOGIC project, a latent difference score model (McArdle, 2001, 2009) could be specified. Using this approach, it was possible to model changes within Openness, Gc, and Gf as latent variables. We could then regress the change in Openness and Gf on the other's baseline score to test the Environmental Enrichment and Success Hypotheses while controlling for their initial overlap as well as for the influence of initial Gc. Moreover, the change in Gc could be regressed on Openness and Gf. Finally, indirect effects could be tested.

The LOGIC Study

The LOGIC study (Schneider & Bullock, 2009) was designed to investigate the long-term development of individual competencies with an emphasis on cognitive aspects. Nevertheless, noncognitive aspects were also part of the design. The sample used here comprised $N = 172$ of the original 239 children. The first assessment took place when the children were approximately 4 years of age. Further assessments took place in several waves. For all assessment waves, intelligence and personality were measured using varying tests. Once the children were old enough to attend school, scholastic achievement was also included. The data have been analyzed according to different research questions (e.g., Asendorpf & van Aken, 2003a, 2003b). Asendorpf and van Aken showed that the personality judgments derived from teacher ratings at the ages of 4 to 6 were predictive of judgments and behavioral observations of

inhibition and aggressiveness, and to antecedents and consequences of school achievement such as IQ test score and cognitive self-esteem up to 9 years later.

Openness predicting changes in Gf (Environmental Enrichment Hypothesis). The study by Raine et al. (2002) was reported above. Those authors found a longitudinal influence of Openness (in the form of curiosity) on intelligence at a very early age. Their explanation was the Environment Enrichment Hypothesis (i.e., being open provides more learning opportunities, and consequently, not only Gc but also Gf is positively affected). As already mentioned, the study unfortunately did not control for possible baseline effects of Gf or Gc on Openness. Using the LOGIC data, the Environmental Enrichment Hypothesis could be tested with a more rigorous design.

Gf predicting changes in Openness (Environmental Success Hypothesis). DeYoung et al. (2005) characterized Openness as a primarily cognitive trait. Based on their findings, it is plausible to assume that Gf not only fosters the acquisition of knowledge but also affects the development of Openness. If one encounters new situations but repeatedly is not able to manage them, it is likely that new situations will be evaded in the future. As a consequence, the person would appear to be low on Openness. On the other hand, successfully dealing with new challenges should go hand in hand with feeling joy and pride. Consequently, seeking such challenging and new situations and stimuli because they are highly rewarding should lead to an increase in Openness (see also the ideas by Cattell discussed above). Using the present data, it was possible to control for the initial overlap and distill the exclusive contribution of Gf on the development of Openness.

Gf and Openness predicting Gc. Regarding a possible impact of Openness on Gc, it was argued above that simply experiencing new situations might not be sufficient to gather Gc.

Instead, employing fluid abilities to make sense of the situation might be a necessary prerequisite. In other words, a possible impact of Openness on Gc might be indirect via an influence on Gf. This would mean that based on environmental enrichment caused by Openness, Gf would be fostered. This change in Gf in turn would foster Gc. In that sense, Openness would have an indirect effect on Gc. This mechanism will be called the Mediation Hypothesis. A similar idea was already explored by Soubelet and Salthouse (2010), who assumed that Openness influences Gc through active engagement. Their results did not support such a claim. However, they did not actually measure active engagement but asked their participants for retrospective self-ratings. Thus, the findings may have been compromised by retrospective distortions. The present study investigated the possible mediating role of Gf in the longitudinal influence of Openness on Gc using ability tests for Gf and Gc and other-ratings for Openness. Especially the use of other-ratings should help to overcome the problems with self-ratings as being just ability ratings or as being biased by retrospective distortion.

Method

Sample and procedure. The sample consisted of N = 172 adolescents (approximately 50% boys). Prior analyses had shown that the sample was reasonably unbiased and attrition was low (19% over 9 years) and unsystematic in previous stages (Weinert & Schneider, 1999). Since such information was not available for the present stage, we used a FIML approach to deal with missing data. Parent ratings for Openness used here were collected when the participants were 17 years old and then again when they were 23. Gf and Gc were also assessed at each measurement point.

Test contents. Descriptive statistics as well as intercorrelations are given in Table 2.

NEO-FFI. A 40-item version of the German NEO-FFI (Borkenau & Ostendorf, 1991) was used to obtain parent ratings. Each parent was asked to rate their child using the eight items for each of the Big 5 domains on a 5-point Likert scale. Ratings for both parents were collapsed across items at both times of measurement. Internal consistency was larger than .90 at both measurement times. Test-retest correlations ranged between .34 and .49 for the mother, father, and combined parent ratings.

Gf. Gf was measured with the German version of the CFT-2 (Cattell & Weiss, 1974). The test consists of the subtests: series (12 items), classification (14 items), matrices (12 items), and topology (8 items). Within the subtest series, the participants are presented with a series of boxes containing abstract figures. The series follows a certain rule and participants have to identify the correct continuation out of five alternatives. The classification subtest asks participants to identify the one box out of five that does not share the common features included in the other boxes. The matrices subtest asks the participants to identify the missing piece in a matrix consisting of four to nine fields out of five alternatives. Within the subtest typology, participants have to identify the one box out of five that has the same pattern of features as a sample box. Cronbach's alpha was .76 at Time 1 and .82 at Time 2.

Gc. In order to obtain a measure for Gc, the vocabulary test of the German version of the Wechsler adult intelligence scales (Tewes, 1991), consisting of 32 items, was used. Internal consistency was larger than .81 in both waves.

Statistical analyses. As can be seen in Figure 2, a latent difference score analysis was performed. In this model, Time 2 measurements for Openness, Gc, and Gf were regressed on their respective baseline score, fixing the regression weight to 1. Additionally, the residual variance was fixed to 0. By doing so, all variance attributable to change was captured by the

latent change variables (ΔO, ΔGc, and ΔGf). All change variables were then regressed on the baseline measures of Openness and Gf to test the Environmental Enrichment and Success Hypotheses as well as the Investment Theory (dashed line in Figure 2). The bold and dotted line within Figure 2 represents the Environmental Enrichment Hypothesis, the combination of both subparts of the dotted line represents the indirect effect of Openness on Gc via a change in Gf, and thus the Mediation Hypotheses. This hypothesis was tested by determining the significance of the indirect path. Furthermore, this model was also compared with a model without a direct path from the Openness baseline to Gc.

In order to keep test power at a maximum, a robust full information maximum likelihood method (MLR) was used to handle missing data (MCAR test: $\chi^2(33) = 48.97$, $p = .036$) because of the nonsystematic sample attrition. In order to interpret model fit, the same guidelines as before were used.

Results

The fit of the full model (see Figure 2) can be interpreted as exact: $\chi^2(1) = .64$, $p = .42$, $RMSEA \approx .000$ (90% CI: .000 - .186), $SRMR = .009$, $CFI = 1.00$. Power was low ($1\text{-}\beta = .1$). The model in which the direct path weight from Openness at Time 1 to ΔGc was fixed to 0 achieved the following fit: $\chi^2(2) = 7.18$, $p = .03$, $RMSEA = .123$ (90% CI: .035 - .225), $SRMR = .049$, $CFI = .969$, which was significantly worse ($\Delta\chi^2 = 6.60$, $\Delta df = 1$, $p = .01$, $\Delta CFI = .031$). Yet, power for this comparison was low .33 (Li & Bentler, 2011). The correlation between the Openness baseline and ΔGc was $r = .37$ ($p < .001$) and dropped to $a < -.01$ (n.s.) in the full model (including the indirect effect via ΔGf). The indirect path from the Openness baseline to ΔGc via ΔGf was marginally significant ($p = .07$, one-tailed), further confirming the Mediation Hypothesis.

The initial overlap between the three constructs was significant and moderate and controlled for in the following analyses. The Environmental Enrichment Hypothesis was supported by a significant path from the Openness baseline to ΔGf. The Environmental Success Hypothesis could not be confirmed. The regression weight from ΔO on Gf was not significant. However, the actual parameter was not 0, indicating that given a larger sample, a small longitudinal influence of Gf on Openness might be found. Finally, the Investment Theory part of the model was also confirmed by a significant path from the Gf baseline to ΔGc. The negative paths from each baseline to the respective change scores show that people starting with higher scores changed less.

Study 2 Conclusions

Study 2 was conducted under a developmental perspective. It aimed to test the longitudinal influences of Openness on Gf and vice versa while controlling for existing overlap between both. Moreover, direct and indirect effects of both constructs on Gc were investigated. All hypotheses were introduced as important expansions of the PPIK model with the exception of the Investment Theory. The results support the Environmental Enrichment Hypothesis and show that Openness positively affects changes in Gf. The Environmental Success Hypothesis could not be confirmed given the sample size. As was the case in Study 1, support for the Investment Theory could be found. The idea that Openness indirectly influences Gc via Gf was supported with results indicating a partial mediation (Mediation Hypothesis). It has to be stressed here that the time interval between the measurement points was 6 years. This means that individual differences in parent-rated Openness explained the changes in Gf that occurred in a time span of 6 years. Those changes in turn at least partially mediated the influence of Openness on Gc.

General Discussion

The present studies were conducted to test theoretical ideas regarding the interplay between Gf, Gc, and Openness to experience. Ideas by Cattell as well as Ackerman's PPIK model served as a starting point. To this end a longitudinal as well as a cross-sectional study was conducted. The findings strongly support the Investment Hypothesis, which is a central part of both Cattell's ideas as well as Ackerman's PPIK model. However, the findings extend the PPIK model by showing that there are developmental influences of Openness on Gf (Environmental Enrichment Hypothesis). Moreover, it could be demonstrated that Openness indirectly influences the development of Gc through the positive influence on the development of Gf (Mediation Hypothesis). Finally, as suggested by Cattell, it could be shown that investigating the interplay between Openness and Gf on immediate Gc related performance proved fruitful.

Environmental Enrichment and Environmental Success Hypotheses. As suggested in the introduction, Openness to experience increases the likelihood of experiencing learning situations. To master such novel situations, Gf can be seen as one important trait. Thus, being open to experience opens up more opportunities to train this specific cognitive ability, an effect that is captured in the Environmental Enrichment Hypothesis. These findings are in line with prior findings by Raine et al. (2002) and Asendorpf and van Aken (2003a) but also extend these because initial overlap between the constructs was controlled for. One important aspect of the analyses conducted here is that Openness was rated by parents. It is reasonable to assume that other-ratings rely more on visible behavior (e.g., Danay & Ziegler, 2011; Ziegler et al., 2010). Considering the age of our sample (17 at Time 1), such overt behavior could be the number of hobbies one has, the number of books one reads, or the number of friends one has. Other behavioral cues could be visits to museums, exhibitions, and concerts, or some kind of actual

artistic engagement. Most of the items used to measure Openness here deal with such aspects of life. An important area for future research consequently is the influence of age. The ages of the participants (i.e., 17 and 23) span a period in which many changes occur: leaving home for university or a job, starting to work, finding new friends, starting a long-term relationship, being economically more independent from one's parents. It is not surprising that open people have many opportunities to seek learning situations across this age span. It would be interesting to investigate this mechanism for younger and older participants. It seems reasonable to assume that there are critical time spans in which the Environmental Enrichment Hypothesis is more or less in vigor. The meta-analysis by Roberts, Walten, and Viechtbauer (2006), which showed that there are age-specific changes in personality, supports the idea of critical time spans. Considering a time span in which people do not have a lot of free choices, it seems plausible that differences in Openness cannot manifest themselves in greatly differing behaviors. Thus, in these times, Openness should not have a great effect on the development of Gf. If this were true, Openness should have especially pronounced effects on the development of Gf in times of change. This would be early adulthood and late adulthood. While people have to grow into a family and job life when they are young, they have to adjust later when they retire or have to deal with losing their partner. All in all, the present data support the assumption of a longitudinal influence of Openness on Gf at least at certain ages.

A likewise influence from Gf on Openness was also hypothesized. This Environmental Success Hypothesis could not be confirmed. One possible reason for the lack of a significant result could be low statistical power. Another factor could be, again, critical time spans. As was discussed above for the influence of Openness on Gf, there might be certain (i.e., critical) time spans during which the influence of Gf on Openness is more likely. Within such time spans, the

environment a person moves about should be relatively new and unknown, requiring a larger amount of reasoning. Considering the age of our sample, one could argue that most of the new situations and information encountered are not overly complex, unknown, or categorically different from well-known situations, calling for little fluid powers. However, especially for younger children, there are numerous situations and chunks of information that are absolutely new, making active cognitive involvement almost mandatory. In that sense, success should be linked to Gf more strongly. As was discussed above, this should foster Openness. Thus, the present results might manifest differently in a considerably younger sample. Empirical support for the idea of critical time periods again comes from a meta-analysis by Roberts, Walton, and Viechtbauer (2006), which revealed the largest changes in Openness during the age periods of 10-22 and 60-70.

Investment Theory. The well-known Investment Theory proposed by Cattell (1943, 1987) and also part of Ackerman's PPIK model finds further support in our analyses: Individual differences in Gf at the age of 17 positively predict Gc at the age of 23. A more detailed look reveals that the Investment Theory is supported by two results. On the one hand, the positive path from the Gf baseline to ΔGc is a clear indicator of the soundness of the hypothesis. However, it can also be seen that the changes in Gf themselves that occur in these 6 years positively affect ΔGc. Thus, there is a baseline influence of Gf as well as an impact of the change in Gf taking place on the development of Gc. This interesting result broadens the understanding of the influence Gf has on Gc.

Mediation Hypothesis. It was hypothesized above that Openness might have an indirect effect on Gc via an influence on Gf. Within the present study, a partial mediation was indeed confirmed. The direct influence of the Openness baseline on ΔGc did not vanish completely as

was the case in Study 1. The larger reliance on visible behavior due to using parent ratings as an indicator for Openness might explain this result. Thus, an influence of Openness on Gc should not be ruled out, but might depend on how Openness is measured. Even so, the amount of ΔGc variance explained by the direct path was rather low at 3%. It is also reasonable to assume that further mediators are missing in the model. One possible candidate would be working memory. Retaining and processing information are functions of working memory (Oberauer, Süß, Wilhelm, & Wittmann, 2008). For working memory to be the missing mediator, several assumptions must be fulfilled. First, it would be necessary that working memory is not isomorphic with Gf. Bühner, Krumm, and Pick (2005) showed that the constructs can be considered distinct despite their shared variance. A second necessary assumption would be differential validity of the constructs. In a study in which multitasking served as the criterion, working memory was an incremental predictor above and beyond Gf, which shows that there can be a specific influence of working memory on other variables (Bühner, König, Pick, & Krumm, 2006). In a different study, Bühner, Kröner, and Ziegler (2008) investigated the relationship between Gf, working memory, and the problem-solving components of rule knowledge and rule application. Whereas previous studies had shown that Gf predicts the amount of rule knowledge acquired in a problem-solving scenario (Kröner, Plass, & Leutner, 2005), the study by Bühner et al. was able to show that this influence actually originates in individual working memory differences. A third assumption that should be met is that working memory has a significant relationship with Gc. This assumption was supported by findings from Wittmann and Süß (1999). A final necessary prerequisite to support the idea of working memory as a missing mediator would be a substantial relationship between Openness and working memory. Empirical evidence also supports this assumption (DeYoung et al., 2005). Therefore, future studies should

try to include working memory to further elucidate the exact mechanism underlying an assumed indirect effect of Openness on Gc.

All in all, it can be concluded that the assumption that Openness leads to changes in Gf, which in turn influence Gc, was supported.

Limitations and outlook. One limiting aspect of this study is that only two measurement points could be used for analyses. Future research should therefore try to use more time points. It also has to be conceded that the age span of the participants covered here usually represents a period of change as was discussed above. Thus, future research should broaden the perspective by systematically varying the age range. Even though other-ratings were used, it would be interesting to test the hypotheses using peer ratings or actual behavioral indicators instead of parent ratings. Despite a time interval of 6 years being exceptionally large even in a longitudinal design, the sample size used here provided limited power; thus, replications in larger samples are needed. Another important aspect is the use of manifest variables for the latent change score models. Given their unreliability, the present findings could be distorted. Considering the reliability estimates calculated for the manifest variables used, this distortion should be minimal, though. Finally, as in Study 1, a vocabulary test was used as an indicator of Gc. Even though McGrew (2009) marked vocabulary as one of the most prominent indicators of Gc, the breadth of the criterion could be criticized. However, since the Gf measure used had only figural content, the supporting findings show that the mechanisms are not simply due to the shared verbal content of the intelligence tests. Nevertheless, future studies should systematically use broader Gc measures.

An integration: The OFCI model. The analyses presented in Studies 1 and 2 were conducted to test possible interactions as well as the longitudinal interplay between Openness

and Gf with Gc as a criterion variable. This was done to test part of the PPIK model but also some theoretical extensions. Below we will propose a model integrating the findings. The Openness-Fluid-Crystallized-Intelligence (OFCI) model should not be regarded as an alternative to the PPIK model summarized above. Instead, the OFCI model is a process model integrating Openness, Gf, and Gc. To describe the complex interplay between these traits, the OFCI model on the one hand differentiates between immediate performance and a developmental perspective. On the other hand, the OFCI model makes specific assumptions: (a) Based on the Environmental Enrichment Hypothesis, a positive longitudinal influence of Openness on Gf is assumed. The idea here is that being open brings about more learning opportunities, which positively affect Gf. (b) Based on the Environmental Success Hypothesis, it is assumed that Gf positively affects Openness because it increases the likelihood of successfully managing new challenges. (c) For both mechanisms, critical time periods should be considered in which the effects might be more or less pronounced. (d) Regarding immediate performance, the OFCI model proposes that higher standings on Openness or Gf potentially dominate the predictive power of the respective other trait when predicting Gc. (e) The OFCI model also includes Cattell's Investment Theory also part of the PPIK model, which says that Gf leads to an accumulation of Gc. (f) The mechanisms described so far explain the bivariate relationships. The OFCI model further claims that Openness also influences Gc via an effect on the development of Gf (Mediation Hypothesis). Finally, the OFCI model goes beyond the present findings and integrates ideas by Cattell and Ackerman that interests also moderate the impact of Openness and Gf on the development of Gc.

The results presented here support most of these hypotheses under a concurrent as well as a longitudinal perspective. Future research should try to test the role of interests within the OFCI model. As Ackerman (1996) pointed out, interests have a profound influence on the development

of knowledge. Including interests would thus be another vital component whose influence is necessary to understand in order to fully capture the processes underlying human learning.

Conclusion

The present findings not only confirmed the previously reported bivariate relationships between Openness, Gf, and Gc (Ackerman & Heggestad, 1997; Ashton et al., 2000), but extended these findings by highlighting the importance of controlling for overlap using adequate designs and using facets as level of analysis. Moreover, specific direct and indirect effects of Openness on Gf and Gc could be confirmed. Finally, the proposed OFCI model integrates these findings and offers a new perspective on the relation between Openness, Gf, and Gc.

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Footnotes

[1] The findings could be replicated with data from Study 2.

[2] The indirect path from Gf to Gc via the change in Openness was not significant.

Table 1

Descriptive Statistics and Bivariate Correlations

	M	*SD*	Gf	Gc	O	O1	O2	O3	O4	O5	O6
Gf	116.74	18.50	1	.25**	.28**	.28**	.05	.10	.10	.35**	.19**
Gc	0.78	0.69		1	.26**	.16*	.03	.13*	.14*	.22**	.31**
O	128.76	16.80			1	.64**	.68**	.60**	.57**	.67**	.55**
O1	21.43	4.78				1	.26**	.32**	.25**	.28**	.21*
O2	23.51	4.89					1	.51**	.17*	.34**	.16*
O3	24.22	4.39						1	.12	.13*	.13*
O4	17.66	4.16							1	.28**	.40**
O5	21.07	5.36								1	.36**
O6	20.86	3.32									1

Note. N = 180. Gf = reasoning as indicator of fluid intelligence (range: 0-180). Gc = vocabulary as indicator of Gc. O = Openness (range: 48 – 240). O1 = Fantasy, O2 = Aesthetics, O3 = Feelings, O4 = Actions, O5 = Ideas, O6 = Values (range: 8 – 40).
*p < .05. **p < .01 (all tests one-tailed).

Table 2

Descriptive Statistics and Bivariate Correlations for Study 2

	M	*SD*	$O_{par\ 1}$	$O_{par\ 2}$	Gf_1	Gf_2	Gc_1	Gc_2
$O_{par\ 1}$ [a]	3.96	.53	1	.49***	.34***	.42***	.49***	.39***
$O_{par\ 2}$ [b]	3.35	.46		1	.28***	.32***	.23**	.26***
Gf_1 [c]	37.78	4.55			1	.76***	.38***	.44***
Gf_2 [d]	39.68	4.73				1	.43***	.48***
Gc_1 [e]	19.74	3.94					1	.70***
Gc_2 [d]	21.70	4.51						1

Note. $O_{par\ 1}$ = Collapsed mean parent rating for Openness at Time 1 age 17 (range: 1-5), $O_{par\ 2}$ = Collapsed mean parent rating for Openness at Time 2 age 23 (range: 1-5), Gf_1 = CFT score Time 1 (range: 0-46), Gf_2 = CFT score Time 2 (range: 0 – 46), Gc = HAWIE-R vocabulary test (range: 0-32). Correlations based on FIML.
[a]n = 149. [b]n = 120. [c]n = 172. [d]n = 145. [e]n = 151.
***p < .001, one-tailed.

Figure 1. Confidence band and regions of significance (upper part) as well as interaction plots (lower part) for the moderating effect of Gf on the correlation between Openness and Gc

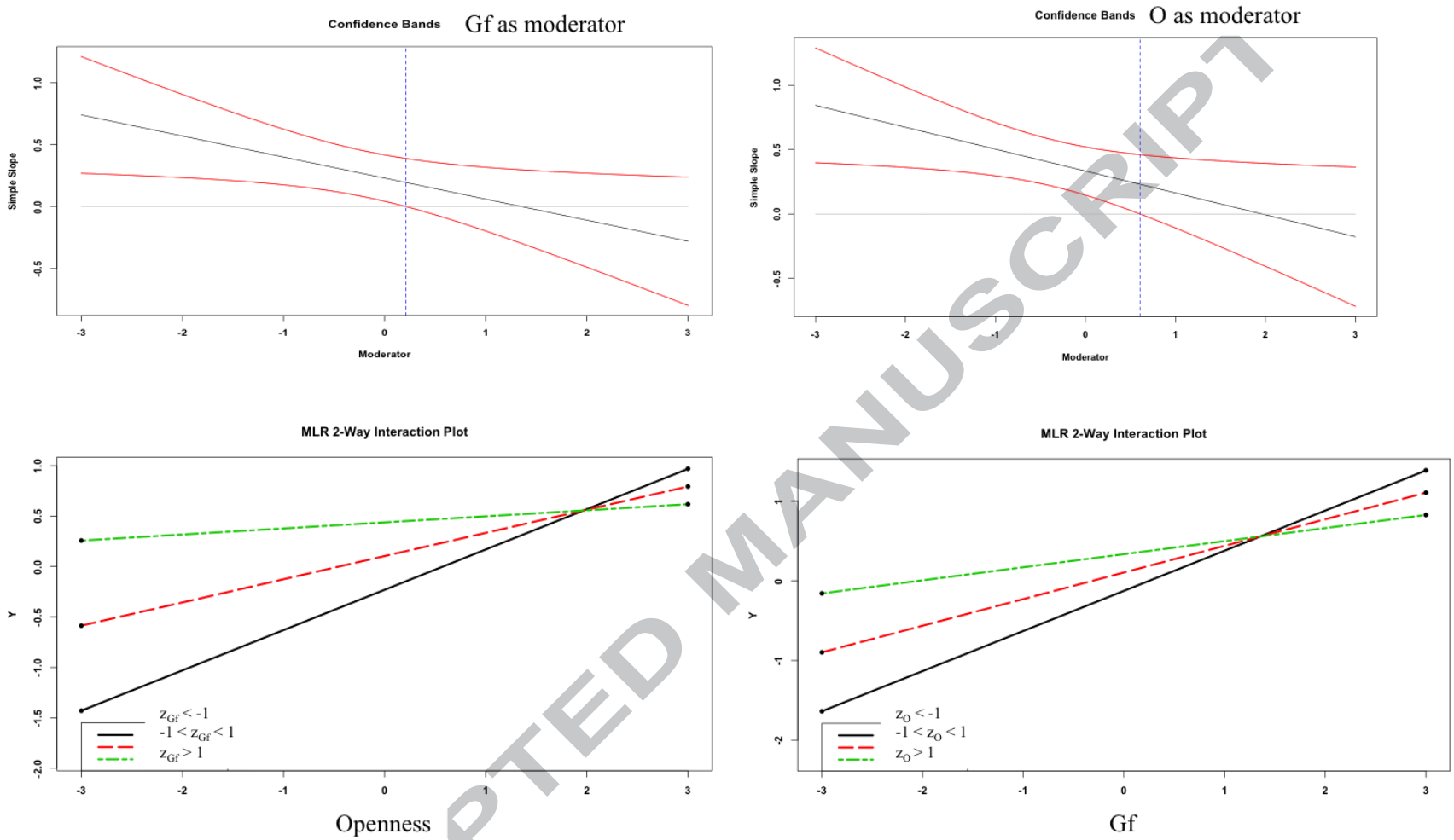
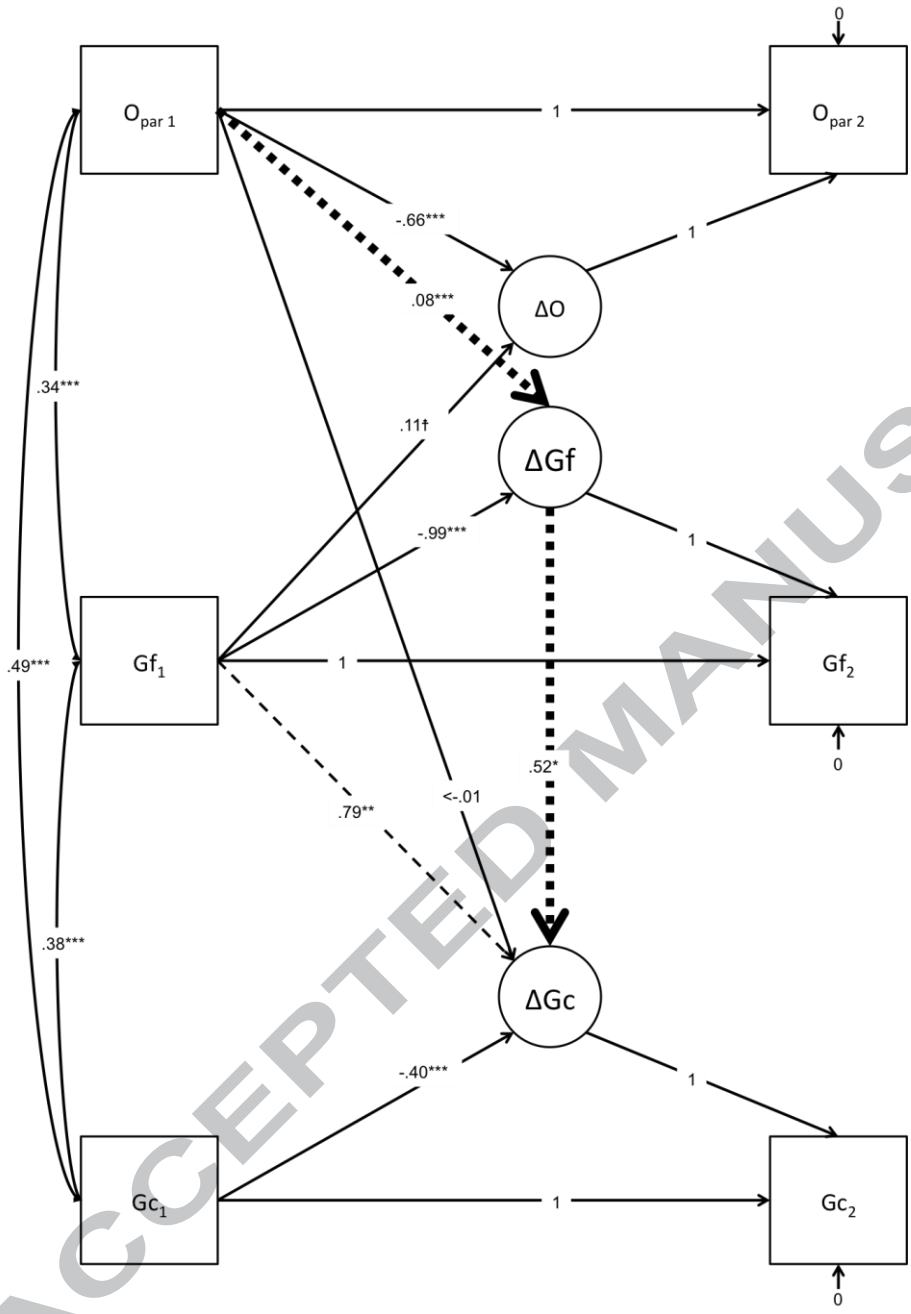
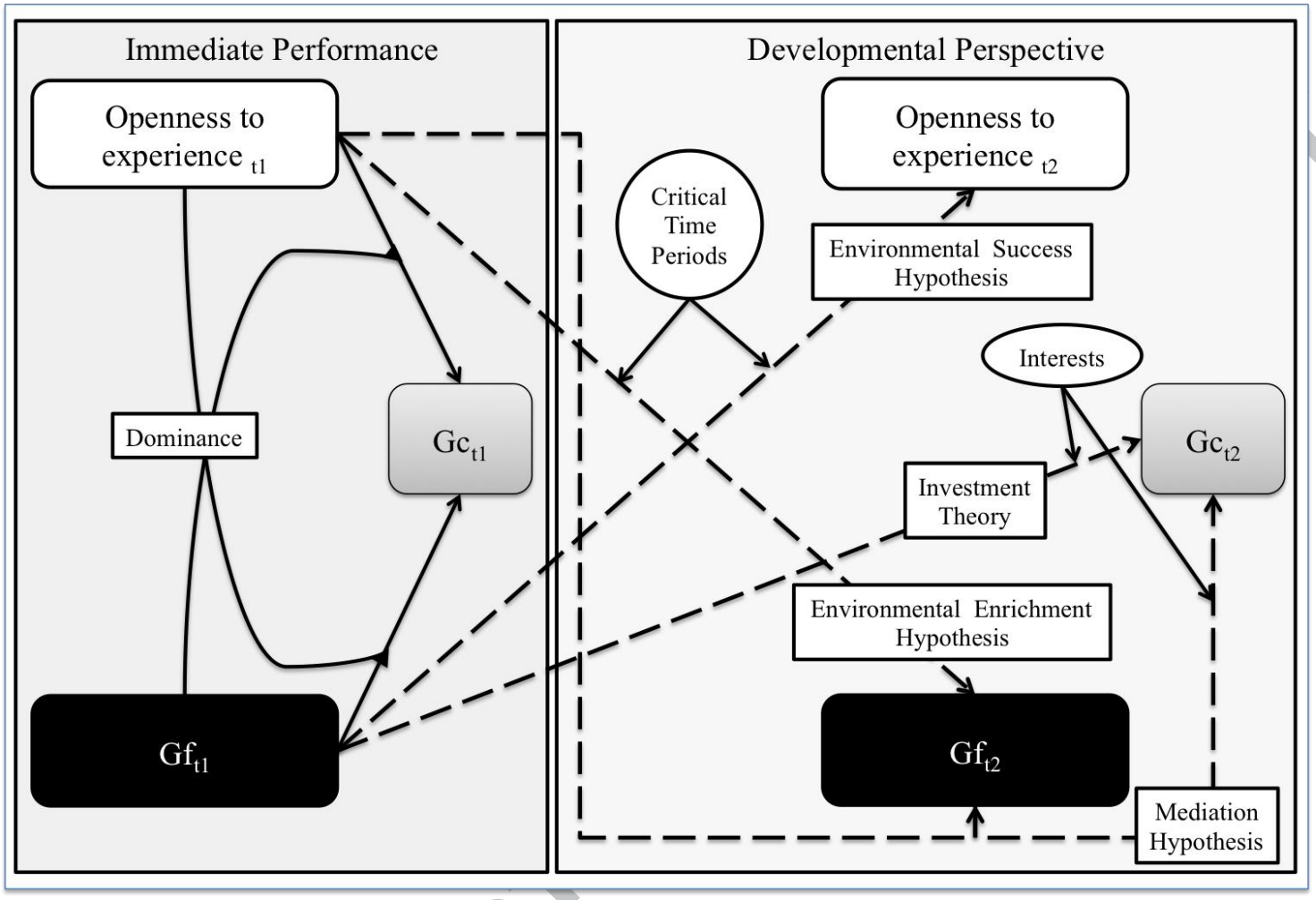


Figure 2. Latent difference score model Study 2 (longitudinal perspective)



$O_{par\ 1}$ = Collapsed mean parent rating for Openness at Time 1, $O_{par\ 2}$ = Collapsed mean parent rating for Openness at Time 2, Gf_1 = CFT score Time 1, Gf_2 = CFT score Time 2, Gc_1 = HAWIE-R vocabulary test as a marker for Gc Time 1, Gc_2 = HAWIE-R vocabulary test as a marker for Gc Time 2. ΔO = Latent change score for Openness. ΔGf = Latent change score for Gf. ΔGc = Latent change score for Gc. Dotted bold line = Environmental Enrichment Hypothesis. Complete dotted line = Mediation Hypothesis. Dashed line = Investment Theory. The value in parentheses represents the R^2 without direct path from the Openness baseline to ΔGc. All significance levels one-tailed.

Figure 3. The Openness-Fluid-Crystallized-Intelligence (OFCI) model



Gf = Fluid Intelligence. Gc = Crystallized Intelligence. Dashed lines indicate longitudinal influences. Direct longitudinal influences of each construct on its time 2 measure are not depicted.

- The interface between Gf, Openness, and Gc is investigated
- Cross-sectionally a main effect for Gf is found and aninteraction between O and Gf
- A latent-change-score model estimates longitudinal effects across a 6 year timespan
- Results confirm the environmental enrichment hypothesis and the Investment theory