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The Openness-Fluid-Crystallized-Intelligence (OFCI) Model and the Environmental Enrichment Hypothesis

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Abstract

The Openness-Fluid-Crystallized-Intelligence (OFCI) model describes how these different constructs interact over time. One fundamental element in the model is the Environmental Enrichment Hypothesis, which states that more Openness leads to more learning opportunities, thereby fostering fluid intelligence (Gf). Indirectly, this positive influence also has a positive effect on crystallized intelligence (Gc). Despite empirical evidence supporting the model as a whole, little is known with regard to the actual mechanisms underlying environmental enrichment. PIAAC (Programme for the International Assessment of Adult Competencies) data (N = 5,465) were used to explore possible behavioral differences that lead to enriched environments for more open people. To this end, we utilized different indicators of reading and calculating behavior. The indicator of Openness used was indeed found to be associated with differences in reading and calculating activities at work and during leisure time. These relations were also shown to be related to the indicator of Gf and indirectly to the indicator of Gc. Theoretical implications and limitations of the study are discussed.

Word count:

Keywords: Openness, reading, calculating, Gf, Gc

The OFCI Model and the Environmental Enrichment Hypothesis

According to Cattell's Investment Theory (1987), fluid intelligence (Gf) promotes the growth of crystallized intelligence (Gc). Further, in Ackerman's (1996) model about Intelligence-as-Process, Personality, Interests, Intelligence-as-Knowledge (PPIK model), intelligence is considered a process, and personality traits, especially Openness and interests, are added as important factors of intellectual development. On the basis of these ideas, Ziegler, Danay, Heene, Asendorpf, and Bühner (2012) developed the Openness-Fluid-Crystallized-Intelligence (OFCI) model, which includes the relationship between Gf and Gc and assigns a central role to Openness. More specifically, Openness is thought to play a key role in one central aspect of the OFCI model: the Environmental Enrichment Hypothesis.

This hypothesis states that Openness fosters the development of Gf. It is assumed that higher Openness leads to more training opportunities, which in turn enrich the environment so that Gf develops positively. However, research has yet to determine which specific behaviors differ in the lives of open people compared with less open people and affect the development of Gf. The aim of the current study was to shine light into this black box by analyzing cross-sectional data from the Programme for the International Assessment of Adult Competencies (PIAAC) study. The next sections describe the OFCI model, the PIAAC study, and how the PIAAC data were used to test the ideas about behavior involved in the Environmental Enrichment Hypothesis.

The OFCI Model

Figure 1 provides a brief overview of the main hypotheses in the OFCI model. The model is divided into two parts. One side presents current relations between abilities and Openness. Specifically, Openness and Gf affect Gc in a positive way. Thus, the higher a person's Openness, the higher the person's Gc. The same holds true for Gf in that high Gf is associated with more Gc. However, there is also an interaction effect in the form of a compensating effect. This dominance effect says that not only are the traits additive, but they also compensate for each other at high levels. So, the effect of one variable disappears just as the other variable exceeds a certain level. Ziegler and his colleagues found this relation in their paper on the OFCI model (2012). Zhang and Ziegler (2016) replicated these results in a large sample of Chinese students across three different content areas.

However, of even greater importance for the current investigation is the second part of the OFCI model, which deals with the interplay between Openness, Gf, and Gc that takes place over time. From this longitudinal perspective, the path from Gf to Gc represents Cattell's *Investment Theory*. Next to this, there are three more paths leading to hypotheses regarding the role of Openness in the model. The *Environmental Success Hypothesis* says that persons with higher ability (Gf) will manage new situations more successfully, and as a consequence of having a positive feeling of success, they are more likely to search for new situations to master in the future (for further supporting evidence see Wettstein, Tauber, Kuźma, & Wahl, 2017). Thus, Gf is considered to influence the development of Openness.

Another path specifies the opposite influence. The idea behind the *Environmental Enrichment Hypothesis* is based on findings by Raine, Reynolds, Venables, and Mednick (2002), who suggested that Openness should provide more learning opportunities and should consequently foster Gf. In addition, Gc should be indirectly affected via this mechanism (*Mediation Hypothesis*). Empirical support for this longitudinal perspective of the OFCI model has been provided by longitudinal data from people in early (Ziegler et al., 2012) and late adulthood (Ziegler, Cengia, Mussel, & Gerstorf, 2015).

Despite this positive support for the general ideas of the OFCI model, it remains unclear exactly how differences in Openness enrich a person's environment and thereby foster Gf. So far, no studies have focused on actual behaviors. It is simply assumed that Openness fosters the development of Gf by making people with higher degrees of Openness select more unknown situations that require Gf to be solved successfully. The current study focuses on the possible mechanisms that lead to enriched environments as posited in the OFCI model. Identifying such mechanisms is an important step in understanding how differences in Openness shape the development of cognitive abilities.

Openness and Environmental Enrichment

The Big Five trait Openness and its nature has been discussed a lot since its postulation. Openness is seen from different perspectives as a personality trait, that is connected to adaptiveness (Specht, Egloff, & Schmukle, 2011), explorative behavior (DeYoung, Grazioplene, & Peterson, 2012), and intellectual interests (e.g. Goldberg, 1999). Depending on the specific focus of the definition, Openness is also Openness to Experience, Culture, Intellect, or Openness/Intellect. In the OFCI model Openness is seen as a personality trait, that energizes people to actively search for new information and new situations as well as a preference for dealing with new information (Ziegler et al., 2012). This definition sets a focus on Openness to Ideas, which former studies of the OFCI model show to be more important than the other Openness facets. That facet is also a defining one in the Openness aspect Intellect. Despite this seeming importance of Openness to ideas or Intellect, we want to note, that we consider the whole domain as important for the OFCI model framework (Ziegler, Schroeter, Lüdtke, & Roemer, 2018).

Openness as a Predictor of Reading and Calculating Behavior

Reading is positively associated with Openness. Kraaykamp and Van Eijck (2005) analyzed the 1998 and 2000 waves from the Family Surveys of Dutch Populations (N = 3,156, ages 18 to 70) to examine the impact of the Big Five on media preferences and cultural participation. Using regression analyses, they found that Openness predicted reading as a preferred leisure activity. In addition, their results showed that "individuals who score high on Openness clearly favor complex and stimulating genres (literature and suspense literature), while they dislike romantic fiction" (p. 1683). Furthermore, reading is an important part of Typical Intellectual Engagement (Arteche, Chamorro-Premuzic, Ackerman, & Furnham, 2009; Wilhelm, Schulze, Schmiedek, & Süß, 2003), a trait that can be seen as one of the facets of Openness (Mussel, 2013). Arteche et al. (2009) reported a correlation between Openness and reading of r = .27 in a sample of 328 students from universities in the US and UK. In addition, Openness was found to correlate with investigative interests (Costa, McCrae, & Holland, 1984). People with intellectual interests value the development and acquisition of knowledge and prefer a job environment where they can do these things, such as in mathematical or scientific work (Holland, 1996, p. 398). This finding is supported by a meta-analysis by Barrick, Mount, and Gupta (2003). Their results showed a moderately strong correlation between Openness and investigative interests.

In summary, we suggest here that one of the mechanisms by which Openness leads to environmental enrichment is that Openness is manifested in differences in reading and calculating activities. In particular, higher Openness should lead to more of these activities.

In the OFCI model, it is also suggested that Openness is about seeking new ideas and situations or information in general. More open people are more likely to select new situations seeking new stimuli, which train Gf because, for example, evaluation and integration of these new stimuli are necessary to deal with new information. This investment of Gf into the understanding and integration of new information is associated with increasing Gc (i.e., acquiring knowledge about the situation that had previously been new). So, this knowledge is associated with specific characteristics of the new information, for example, the new information people obtain when visiting a zoo will extend their knowledge about animals (e.g., by understanding the difference between rabbits and hares and integrating this into one's knowledge structures).

As shown above, Openness affects the choice of one's reading material with people higher in Openness favoring intellectually stimulating genres. It can be assumed that the information contained in such material includes new information that needs to be understood and integrated. With regard to the OFCI model, we therefore expect that not only will reading be related to Openness but that it will also act as a mediator between Openness and Gf and thereby between Openness and Gc. Considering the domain specificity of Gc (Schipolowski, Wilhelm, & Schroeders, 2014), it is further expected here that these relations will mostly occur for verbal aspects of Gc.

Despite the lack of empirical evidence regarding similar processes between Openness and calculating, it is reasonable to expect similar mechanisms to be at work.

Again, referring to the faceted nature of Gc, these relationships are expected to occur primarily for the numeracy-related aspects of Gc. This idea will be explored in the analyses of this paper.

PIAAC

The Programme for the International Assessment of Adult Competencies (Rammstedt, 2013; Zabal et al., 2014) is a long-term study initiated by the Organization for Economic Cooperation and Development (OECD), which focuses on the development of adult competencies and is conducted by the Leibniz Institute for Social Science (GESIS). Thereby, the concept of the survey is based on people's real lives. So, priority is given to the skills required in the labor market that are important for accessing resources and services in society in general. The first wave of the PIAAC study focused on the competencies literacy, numeracy, and problem solving in technology-rich environments (PS-TRE). These were chosen as a representative subset of the skills focused. Next to these competencies, PIAAC includes variables that influence the development of skills. Therefore, a lot of information about education, family background, personality, as well as activities during leisure time and at work (e.g., reading and calculating) has been collected to create a comprehensive picture of each person's competences and behaviors in real life.

PIAAC Constructs and the OFCI Model

PIAAC and research on the OFCI model pursue a common goal: the clarification of the development of cognitive abilities. Even though the term competence is used in PIAAC, there is a strong conceptual overlap with cognitive abilities. Koeppen, Hartig, Klieme, and Leutner (2008) defined competence as "domain-specific cognitive dispositions that are required to successfully cope with certain situations or tasks, and that are acquired by learning processes" (p. 68). Moreover, several theoretical papers have come to the conclusion that competencies and abilities share variance and strongly overlap (Monnier, 2015; Wilhelm & Nickolaus, 2013). Finally, it has been suggested that competencies represent continuous traits rather than dichotomous or categorical classes (Blömeke et al., 2014; Blömeke, Gustafsson, & Shavelson, 2015). Thus, PIAAC data work well for testing hypothesis generated from the OFCI model regarding cognitive abilities, even though the competency measures are not pure cognitive ability tests.

As already mentioned, next to the more cognitive-ability-like competencies, PIAAC also includes some variables that could influence the development of these abilities, including information about how much a person engages in reading and calculating activities. This study specifically focuses on certain parts of the OFCI model and therefore needs: (a) an indicator of Gf, (b) an indicator of Gc, and (c) an indicator of Openness to Ideas. At the same time, the study tries to shed light on the potential mechanisms that underlie environmental enrichment by integrating (d) information about reading and calculating activities as concrete behaviors that are expected to differ between people with high versus low Openness. Therefore, we used the abilities measured in PIAAC as indicators of fluid and crystallized intelligence and information from the background questionnaire to operationalize Openness and reading and calculating behaviors. The next sections describe the extent to which competencies measured in the PIAAC can be seen as indicators of the constructs in the OFCI model.

Fluid Intelligence: Problem Solving in Technology-Rich Environments (PS-TRE)

Problem solving (PS-TRE, PIAAC Expert Group in Problem Solving in Technology-Rich Environments, 2009) served as an indicator of Gf in this study. According to the PIAAC Expert Group in Problem Solving in Technology-Rich Environments (2009), problem solving in technology-enriched environments involves the use of digital technology, communication tools, and networks to acquire and evaluate information, communicate with others, and perform practical tasks. It is said that the cognitive processes needed to solve the tasks are (a) goal setting and progress, (b) planning and self-organizing, (c) acquiring and evaluating information, and (d) making use of information. These processes, especially the last two, strongly resemble the definition of fluid intelligence given by McGrew (2009): “the use of deliberate and controlled mental operations to solve novel problems […]. Mental operations often include drawing inferences, concept formation, classification, generating and testing hypothesis, identifying relations, comprehending implications, problem solving, extrapolating, and transforming information” (p. 5). Furthermore, Greiff et al. (2014) summarized recent research about problem solving and concluded that problem solving is an important part of fluid intelligence. In addition, Bühner, Kröner, and Ziegler (2008) supported the idea by showing a strong overlap between indicators of Gf and indicators of problem solving.

Crystallized Intelligence: Literacy and Numeracy

In this paper, we used literacy (PIAAC Literacy Expert Group, 2009; Rammstedt, 2013; Zabal et al., 2014) and numeracy (PIAAC Numeracy Expert Group, 2009; Rammstedt, 2013; Zabal et al., 2014) as indicators of Gc. The PIAAC

Literacy Expert Group (2009) defines literacy as “understanding, evaluating, using and engaging with written text to participate in society, to achieve one’s goals and to develop one’s knowledge and potential” (p. 8). Literacy tasks usually include a text as the stimulus and one or more questions about the text that can often be answered by highlighting parts of the text. With regard to the PIAAC Literacy Expert Group (2009), cognitive processes that are needed to answer questions accurately are (in order of difficulty) (a) access and identify, (b) integrate and interpret, and (c) evaluate and reflect. According to McGrew (2009, p. 5) reading and writing (Grw) include, amongst others, reading, decoding, and reading comprehension and are part of Gc in Carroll’s Three Stratum Model. In addition, Schroeders, Bucholtz, Formazin, and Wilhelm (2013) showed that a latent comprehension factor based on reading and viewing comprehension can be accounted for to a great extent by science knowledge. Therefore, we used literacy as an indicator of Gc in this study.

In addition to literacy, we used numeracy as another indicator of Gc. The PIAAC Numeracy Expert Group (2009) defines numeracy as “the ability to access, use, interpret, and communicate mathematical information and ideas, in order to engage in and manage the mathematical demands of a range of situations in adult life” (p. 6). Numeracy tasks consist of figures, tables, or texts as stimuli and questions that can be solved with the help of a calculator. The numerical result has to be entered into a field next to the question. The cognitive processes needed to answer questions accurately are (in order of difficulty): (a) identify, locate, and access, (b) act upon use, (c) interpret, evaluate, and analyze, and (d) communicate. Rindermann, Flores-Mendoza, and Mansur-Alves (2010) substantiated the use of numeracy as an indicator of Gc. They argued that the quantitative relations that are needed to solve tasks involve knowledge learned in school. According to McGrew (2009), Carroll included math achievement factors in the abilities that fall in the domain of knowledge and achievement. In the Carroll-Horn-Cattell model, this factor is called quantitative knowledge and “represents an individual’s store of acquired mathematical knowledge, not reasoning with this knowledge” (McGrew, 2009, p. 6). Thus, there is sufficient support for choosing numeracy as a further indicator of Gc.

Operationalization of Openness, Reading, and Calculating Behavior

The PIAAC study focuses not only on cognitive abilities but also on variables that could influence the development of these abilities. Among these variables is information about peoples’ personality, including information about a person’s typical behavior regarding learning situations as well as the amount of reading and calculating they tend to engage in. The information fits well with the OFCI model because it includes a personality measure that is indicative of Openness as well as measures of concrete behavior that could underlie environmental enrichment.

The OFCI model promotes the role of Openness in the development of Gf and Gc (Ziegler et al., 2012). Thus, regardless of the specific terminology (see above), it is important for the operationalization of Openness to describe a person as curious about new information or situations, actively searching for new information, and having a preference for dealing with new information. In the PIAAC survey, there is a scale called learning strategies (Allen et al., 2013), which consists of six items that closely reflect this personality description (e.g., “I like learning new things” and “When I come across something new, I try to relate it to what I already know”). All six items can be found in Table 1. Based on the opinions of the involved authors, these items were judged to capture Openness and specifically Intellect. The latent correlation of this measurement of Openness and the Openness score derived from the Short Big Five Inventory (BFI-S, Lang, John, Lüdtke, Schupp, & Wagner, 2011) from the 2014 PIAAC wave was r = .51 which further supports this notion. In fact this matches the meta-analytically based convergent validity of Openness test scores (Pace & Brannick, 2010).

PIAAC also focuses on concrete behavior that could influence the development of cognitive abilities such as numeracy, literacy, or PS-TRE. To achieve this, the background questionnaire includes questions about intellectual behavior at work and during leisure time. The frequency of different reading and calculating activities at work and during leisure time is assessed. Regarding reading activities, questions are about reading (a) directions and instructions, (b) letters, memos, and mail, (c) newspapers or magazines, (d) professional journals or publications, (e) books (fiction or nonfiction but not for one’s job or school), (f) manuals or reference material, (g) financial statements, and (h) diagrams, maps, or schematics. Questions about calculating include information about the frequency with which one (a) calculates costs or budgets, (b) uses or calculates fractions or percentages, (c) uses a calculator, (d) prepares charts, graphs, or tables, (e) uses simple algebra or formulas, and (f) uses advanced math or statistics. In this study, the information about reading and calculating activities was used as a mediator between Openness and Gf, thereby testing for the specific, theoretically informed mechanisms that could underlie environmental enrichment.

Aims of the Study

The OFCI model is a process model describing the developmental interplay between Openness, Gf, and Gc. One aim of this study is to produce the expected relations using population-representative data from the PIAAC study. In this paper, we specifically focus on one part of the OFCI model: the Environmental Enrichment Hypothesis. We suggest that Openness has a positive influence on Gf by providing an enriched environment with more training opportunities. Through its influence on Gf, Openness is also expected to indirectly influence Gc. The OFCI model, including the Environmental Enrichment Hypothesis, has been previously supported (Ziegler et al., 2015; Ziegler et al., 2012). However, the specific mechanisms underlying environmental enrichment have not been tested.

This study tries to provide first ideas about such mechanisms by looking at reading and calculating. Both activities have been shown to be related to Openness and can be considered as cognitive tasks. In line with this idea, we test two models in this paper. The difference between the two models is that in the first one, reading mediates the effect of Openness on cognitive abilities, where literacy is the indicator of Gc. In the second model, calculating activities are the mediator in a model in which numeracy is the indicator of Gc. In both cases, we distinguish between activities at work and during leisure time.

In addition, we also test a model with a more general indicator of Gc. In this model, the two indicators (i.e., numeracy and literacy) are combined into one latent variable for Gc. Also, both mediators (i.e., reading and calculating) are included in the model as latent variables in order to control for potential overlap. This more general model is used to compare reading and calculating as mediators. In addition, the specific activities (e.g., reading books or magazines) are compared in the model to obtain a better understanding of the environmentally enriching effects of reading and calculating activities.

Method

Sample and Procedure

In this study, we used data from the German PIAAC sample (Rammstedt, 2013; Zabal et al., 2014). PIAAC compares job-specific competencies of adults across different countries in regular waves. The first wave was collected in 2012. These data were used here.

The German PIAAC sample consisted of adults between the ages of 16 and 65 years, thus representing the occupationally active population. Data collection was based on a two-stage stratified and clustered sampling design. In the first stage, municipalities, and in the second stage, individuals were randomly selected from registry data. Nationality, resident status, or language skills did not impact a person's selection. The data included 5,465 persons who were representative of Germans between the ages of 16 to 65 years (Rammstedt, 2013; Zabal et al., 2014).

One hundred twenty-nine trained interviewers administered the tests in participants' homes. The first part of the procedure was a personal standardized interview that measured background information. After the interview, competencies were measured on a computer or, in cases where the person was not able to handle a computer mouse, with a paper-pencil-test. The assessment was organized in modules. In the first module, items from one of the three domains (i.e., literacy, numeracy, or PS-TRE) were selected. In the second stage, one of the remaining domains was chosen. During the assessments, participants worked on their own. Interviewers monitored their progress and provided the materials. There was a time restriction for the tasks. On average, 80 to 95 min were needed for the whole assessment, with between 30 to 45 min taken up by the background questionnaire.

Measures

Ability measures.

Crystallized intelligence: literacy and numeracy. The literacy tasks included a text as the stimulus material and one or more items that asked questions about the text and could often be answered by highlighting parts of the text (PIAAC Literacy Expert Group, 2009; Rammstedt, 2013; Zabal et al., 2014). Altogether, the literacy assessment included 52 items. The numeracy tasks (PIAAC Numeracy Expert Group, 2009; Rammstedt, 2013; Zabal et al., 2014) consisted of figures, tables, or text as the stimulus materials and items that could be solved with the help of a calculator. The numerical result had to be entered into a field next to the question. Altogether, the numeracy test included 52 items. We used all 52 items here to specify a measurement model for each variable.

Problem solving in Technology-Rich Environments (PS-TRE). Problem solving in technology-rich environments (PS-TRE) included 24 items in 14 scenarios that have to be solved with a computer (PIAAC Expert Group in Problem Solving in Technology-Rich Environments, 2009; Zabal et al., 2014). All 24 items were used here to specify the measurement models. An example for such a scenario is provided by OECD (2012): Participants see a webpage with the title “websearch”, that includes links to five different job portals. To solve the question, that is displayed next to the window with the webpage, they have to use tools and functionalities of webpages (e.g. clicking on a link). In that case, they have to find out, which portals do not require registration or paying fees and mark the appropriate links to give the answer to the question (for further information see (OECD, 2012)).

Background questionnaire. The background questionnaire (Zabal et al., 2014) was developed by the International Consortium (Allen et al., 2013). General information was recorded on, for example, a person's age and gender as well as details about (a) education and training, (b) recent and current work, and (c) social background. In addition, the actual use of certain skills at work and during leisure time was illuminated. This last information given in the background questionnaire was used in our study as (a) indicators of Openness and (b) to specify habits that represent environmental enrichment (i.e., reading and calculating behaviors).

The background questionnaire included six items that refer to a person's typical behavior in learning situations. Specifically, every item is a statement about a person's habits in dealing with problems and tasks that have to be rated regarding the person's own standing on these behaviors (1 = *not at all*, 5 = *to a very large extent*). All six items can be found in Table 1.

Another part of the background questionnaire asked participants how often they typically carry out certain tasks at work, for example, how often they work with colleagues (1 = *never*, 5 = *every day*). The questions we focused on here were about reading (e.g., frequency of reading books at work) and handling numbers (e.g., frequency of drawing diagrams). These topics were also the subjects of questions about leisure activities. Both scales, calculating at work and calculating during one's leisure time, were operationalized by six items each. All items were about the specific use of calculation habits (e.g., "Outside your work, how often do you usually prepare charts, graphs or tables?”). Eight other items were used to assess reading skills at work and during leisure time. These items asked for specific reading habits (e.g., “In your current job, how often do you usually read articles in newspapers, magazines, or newsletters?”). All questions, for reading as well as for calculation skills, were answered with frequency information (1 = *never*, 2 = *less than once a month,* 3 = *more than once a month and less than once a week*, 3 = *more than once a week but not daily,* 5 = *daily*).

Descriptive statistics and reliability estimates for all variables can be found in Table 2.

Statistical Analyses

We used R (R Core Team, 2014b) to compute all analyses (data were imported using the package foreign, R Core Team (2014a). Descriptive statistics were calculated with the package psych; (Revelle, 2014). The main focus of the analyses was to test the structural equation models (implemented with the package lavaan; Rosseel, 2014). The analyses were divided into several steps. The starting point of this process was to test the measurement models for literacy, numeracy, and PS-TRE. In a next step, we tested the measurement models for the indicator of Openness as well as for the skills. Finally, for reading and calculating, one model each was created for activities at work and one each for activities during leisure. In addition, we estimated a weighted McDonald’s Ω_w (Brunner & Süβ, 2005) for all latent variables.

After testing all measurement models, we tested the structural models. Three different models were of interest (Models A, B and, C, see Figures 2 - 4). All models represented the complete OFCI model. Thus, the relation between the indicator of Openness and the indicator of Gc mediated by the indicator of Gf was common to all models, and problem solving served as the indicator of Gf in all models. Furthermore, the models specifically focused on the mechanisms underlying environmental enrichment. In order to achieve this, we specified an indirect effect of the indicator of Openness on the indicator of Gf that represented activities leading to environmental enrichment.

Models A (see Figure 2) specified reading as a mediator and included literacy as an indicator of Gc in order to account for the faceted nature of Gc. The effect of calculating activities as a mediator between the indicator of Openness and the indicator of Gf was the focus of Models B (see Figure 4). Here, numeracy was used as an indicator of Gc. Next to the specific approaches tested in Models A and B, the last model was more general. Models C (see Figure 6) combined the two indicators of Gc (i.e., numeracy and literacy) into one variable indicating Gc. Also, both mediators (i.e., reading and calculating) were specified. Model C included comparisons of all four mediated effects of Openness on cognitive ability. In addition, two-sided confidence intervals (α = .05) were calculated for all of the loadings of the reading and calculating items to distinguish the importance of specific activities in environmental enrichment in the OFCI model. In each model, we also tested the complete indirect path from the indicator of Openness to the indicator of Gc, reflecting the idea underlying the mediation hypothesis.

To maximize power for all following analyses, we utilized the complete sample and dealt with missing data by using a full information maximum likelihood method. At the same time we estimated power using the package semTool (Pornprasertmanit, Miller, Schoemann, & Rosseel, 2013) for the structural equation model with the worst RMSEA. This procedure is based on MacCallum, Browne, and

Sugawara (1996) and tests the power to detect a critical RMSEA difference.
For the current analyses, the worst RMSEA was .139. The power to detect a critical difference to the threshold of .06 was approximately 1.

The assessment of the goodness-of-fit of all models was guided by Hu and Bentler (1999) recommendations. Thus, the Comparative Fit Index (*CFI* ≈ .95), the Standardized Root Mean Square Residual (*SRMR* ≤ .09), and the Root Mean Square Error of Approximation (*RMSEA* ≤ .06) were used. In case of model misfit, model alterations were specified to ensure that the parameters we interpreted were not biased by model misfit (Heene, Hilbert, Draxler, Ziegler, & Bühner, 2011). To prevent an overfitting of the model to data, the model alterations were also guided by therorical considerations about the reason for misfit.

Results

First, we present the measurement models. Then, we present the results of our tests of the different structural models. Descriptive statistics of all latent variables are shown in Table 2.

Measurement Models

Table 3 shows the model fits for all measurement models. Standardized path coefficients can be found in the Appendix (Table A).

As can be seen, the fit for the measurement model for the indicator of Openness was not acceptable before adding a correlation between two of the six residuals. Both items referred to an analyzing aspect (to get to the bottom of difficult things and to figure out how different things fit together). The correlation between the two residuals was $r = .34$. The standardized path coefficients of all manifest variables ranged from β = .58 to β = .72. The construct reliability of the indicator of Openness was Ω_w = .80.

Also, for literacy, a modified model was specified because the model consisting of 52 manifest variables without any correlated errors yielded an unacceptable model fit. A correlation between two item residuals had to be added. Both items belonged to the same item block and thus referred to the same text (Lakeside Fun Run). The correlation between these residuals in the modified model was r = .63. Standardized path coefficients ranged from β = .18 to β = .71. The construct reliability of literacy was Ω_w = .95.

The measurement model for numeracy had an acceptable fit without modifications. For numeracy's items, the standardized path coefficients ranged from $\beta\lambda$ = .20 to β = .66. In the case of PS-TRE, they ranged from β = .46 to β = .70. The construct reliability for numeracy was Ω_w = .94, and for PS-TRE, it was Ω_w = .89. Thus, modified models for the indicator of Openness and literacy as well as the specified models for numeracy and PS-TRE yielded acceptable fits.

For the models for reading (at work and during leisure), modified models were constructed by adding error correlations between similarly worded items (Model A: reading books and manuals; Model B: reading magazines and professional journals). The same applied to the models for calculating at work and during leisure time, for the items preparing charts and using advanced mathematics as well as calculating budgets and using fractions/percentages. In addition, for calculating budgets at work and using a calculator at work, we added an error correlation. As Table 2 shows, the final models had an acceptable fit. Standardized path coefficients ranged from β = .44 to β = .75 for reading at work, from β = .26 to β = .63 for reading during leisure time, from β = .36 to β = .80 for calculating during leisure time, and from β = .46 to β = .80 for calculating at work.

Model A: Reading as a mediator. Model A (see Figures 2) illustrates the influence from the indicator of Openness via problem solving as indicator of Gf through to literacy. The model includes a direct path from the indicator of Openness on literacy. Model A (Figure 2) had an adequate model fit (see Table 4). The effect of the indicator of Openness on reading at work was descriptively smaller (β = .40) than the one on reading during leisure time (β = .58). The same held true for the impact of these variables on problem solving: reading at work (β = .15) had a smaller effect than reading during leisure time (β = .34). All indirect as well as direct paths were significant ($p < .001$). In addition, it can be seen that the direct influence from the indicator of Openness to literacy was strongly reduced by the mediations (from β = .32 to β = .11[1]) but remained significant. As expected, literacy was related to problem solving (β = .83). These results support that the impact of the indicator of Openness on problem solving as an indicator of Gf and indirectly on literacy as an indicator of Gc was partially mediated by reading at work and during leisure time. Thus, the higher persons score in the indicator of Openness, the more they read at work and during their leisure time, which goes along with higher ability in PS-TRE as an indicator of Gf and also with higher literacy.

Model B: Calculating. As can be seen in Figures 4, Models B tested the path from the indicator of Openness to numeracy mediated via calculating behaviors and problem solving. The model fit was acceptable (see Table 4). Model B revealed an indirect (β = .29) as well as a small direct (β = .14) path of the indicator of Openness to numeracy as the indicator of Gc. The relation between the indicator of Openness

[1] This is a zero-order correlation. See also Table 5.

and the frequency of calculating activities was moderate for both calculating activities at work (β = .35) and calculating activities during leisure time (β = .38). Also the impact of calculating activities on problem solving was moderately high for both ways of using numerical skills (β(work) = .23, λ (leisure) = .31). Like all other paths in the model, both indirect paths were significant (p < .001). As expected, the impact of problem solving on numeracy was high (λ = .75). This result suggests that the impact of the indicator of Openness on the indicator of Gf and indirectly on the indicator of Gc is mediated by calculating activities at work and during leisure time. Higher scores in the indicator of Openness were associated with more calculating activities during leisure time and to a job that requires more calculating activities. This enhanced use of numerical skills was associated with higher ability in problem solving and with higher numeracy.

Model C: General model. Model C, as illustrated in Figures 4 (see Table 4 for the model fit), combines the different mediators and different indicators of Gc from Models A and B. Thus, the indirect impact of the indicator of Openness on that broader indicator of Gc is mediated by the two types of reading and calculating as well as by problem solving. The model fit was acceptable. Gc loaded literacy (β = .96) as well as numeracy (β = .91). There was a small but significant direct effect from the indicator of Openness to the indicator of Gc (β = .11). The zero-order correlation between the indicator of Openness and the indicator of Gc was .32. Looking at the impact of the indicator of Openness on reading and calculating activities, it could be seen that reading during leisure time (β = .59), reading at work (β = .46), calculating at work (β = .42), and calculating activities during leisure time (β = .40) were moderately related to the indicator of Openness. The impact of these variables on problem solving ranged from β = .11 for calculating at work and reading during leisure time, to β = .17 for reading at work, to β = .25 for calculating in leisure time. All paths in the model were significant (p < .001). The zero-order correlations between the behaviors and the indicator of Gc can be found in Table 5. Similar to Models A and B, the relation between Gf and Gc was high (β = .85). The path from the indicator of Openness to the indicator of Gc was mediated by all behaviors used to a comparable degree (reading at work: $\beta_{a1*b1*c}$ = .07, reading during leisure time: $\beta_{a2*b2*c}$ = .07, calculating at work: $\beta_{a3*b3*c}$ = .04, reading during leisure time: $\beta_{a4*b4*c}$ = .09, all comparisons: p >.001).

We were also interested in which concrete reading and calculating activities were most important in the OFCI model. Thus, we compared the loadings for the reading and calculating items. In the case of reading during leisure time, reading diagrams, maps, or schematics (β= .67, 90% CI [.58, .76]), manuals or reference material (β = .59, 90% CI [.51, .67]), and professional journals or publications (β = .59, 90% CI [.50, .68]) were most representative, followed by reading letters, memos, and mail (β = .51, 90% CI [.43, .59]), directions and instructions (reference path, β = .48), newspapers or magazines (β = .34, 90% CI [.28, .41]), and books (β = .32, 90% CI [.23, .41]). Least important was the reading of financial statements (β= .24, 90% CI [.19, .30]). For reading at work, a different picture emerged: Most representative for reading were reading letters, memos, and mail (β = .74, 90% CI [.62, .87]), and professional journals or publications (β = .73, 90% CI [.62, .83]), followed by reading newspapers or magazines (β = .72, 90% CI [.60, .84]), manuals, or reference material (β= .60, 90% CI [.51, .70]), diagrams, maps, or schematics (β= .54, 90% CI [.44, .64]), directions and instructions (reference path, β = .48), and books (β = .47, 90% CI [.39, .54]). Least important here was reading financial statements (β = .46, 90% CI [.36, .56]). In the case of calculating activities, the picture was similar for work and leisure: Most relevant were activities such as using simple algebra or formulas (leisure: β = .78, 90% CI [.62, .93], work: β = .81, 90% CI [.69, .94]), and using or calculating fractions or percentages (leisure: β = .75, 90% CI [.61, .89], work: β = .80, 90% CI [.69, .91]). Less important activities during leisure time were preparing charts, graphs, or tables (β = .67, 90% CI [.57, .77]), using advanced math or statistics (β = .59, 90% CI [.50, .67]), using a calculator (β = .55, 90% CI [.44, .67]), and calculating costs or budgets (reference path, β = .38). At work, using a calculator (β = .67, 90% CI [.57, .77]) was the next most important activity after the use of fractions and simple algebra. The preparing of charts, graphs, or tables (β = .64, 90% CI [.55, .72]) and the use of advanced math or statistics (β = .50, 90% CI [.45, .54]) were less relevant. Least important of all of the calculating activities at work was the calculation of costs or budgets (reference path, β = .47).

Beyond the results of the previous models that showed that the influence of the indicator of Openness on indicators of intelligence was mediated by reading (Model A) and numerical skills (Model B), these final results illustrate that both kinds of behaviors used at work and during leisure time are generally important factors. A closer look at specific behaviors showed that not all kinds of reading and calculating behaviors might be equally important though. In the case of reading during leisure time, reading journals, manuals, and diagrams were most relevant, and at work, it was the reading of emails and magazines or newspapers. Regarding calculating activities, there was not a big difference: In both cases, calculations involving fractions or percentage as well as simple algebra were most important.

Discussion

In the current paper, PIAAC data were used to replicate the OFCI model in general and to inspect possible mechanisms underlying the Environmental Enrichment Hypothesis in particular (Openness-Fluid-Crystallized-Intelligence model, Ziegler et al., 2012). The OFCI model was developed by Ziegler and his colleagues and was based on ideas by Cattell (1987) and Ackerman (1996). Not only is the model about how Gf (fluid intelligence) influences Gc (crystallized intelligence), but it also includes Openness as another key construct in this interplay. The Environmental Enrichment Hypothesis states that Openness positively affects the development of Gf by leading to more learning opportunities. It is assumed that more open persons like to search for new situations and information, thereby stimulating and training their fluid abilities. The longitudinal influence of Openness on Gf has been shown in several studies (Ziegler et al., 2015; Ziegler et al., 2012). However, the concrete mechanisms underlying environmental enrichment have never been discussed or tested. The current study distinguished between reading and calculating as two possible mechanisms underlying environmental enrichment. We tested these hypotheses. The results confirm both activities and also highlight their relevance in leisure and work.

Openness, Gf, and Gc

In line with Cattell (1987), we found a strong association of an indicator of Gf and indicators of Gc (numeracy and literacy). According to Cattell, the reason for this effect is that Gf is invested into the acquisition of Gc. Furthermore, Ackerman (1996) said that personality plays an important role in the development of cognitive abilities. The OFCI model (Ziegler et al., 2012) further suggests that Openness —especially

Openness to Ideas—is the crucial personality trait within the context of cognitive development. The results of the current study further support this idea. In all three models, indicators of Gf and Gc were associated with the indicator for Openness to Ideas.

Environmental Enrichment Hypothesis

The current study extends previous findings on the OFCI model (Ziegler et al., 2012) by adding a mediator variable between Openness and cognitive abilities to represent environmental enrichment (search for information or situation). In order to prove this idea of mediation by environmental enriching activities, we also tested models, which included direct paths from Openness to ability. Results support a preference for models with these bypasses and so indicate a partial mediation by reading and calculating activities at work and during leisure.

Thus, results support the Environmental Enrichment Hypotheses made in the OFCI model. Here, a positive influence of Openness on Gf and Gc is not only described, but also the relationship is explained by environmental enrichment, which means that more open people prefer specific environments, which goes along with learning opportunities fostering Gf and Gc. Results indicate reading and calculating activities at work and during leisure as activities, which can serve as learning opportunities, but also show, that this is only a part of possible activities and by that way gives room for the addition of further activities enriching one's environment.

Specific effects of reading and calculating. Two of the specific activities focused on here are closely related to a specific facet of Gc. Reading is clearly closer to the verbal aspects of Gc (here literacy), and calculating is closer to the numerical or quantitative aspects of crystallized intelligence (here numeracy). Results show that reading (partially) mediates the path from an indicator of Openness to an indicator of Gf. Thus, the hypothesis is supported, that people with higher Openness would read more during their leisure time and at work, and this would to foster Gf. This finding is in line with the literature on Openness and similar constructs (Mussel, 2013) and reading activities (Wilhelm et al., 2003). Thus, one important mechanism underlying environmental enrichment has been identified: reading.

The current study extends knowledge on this topic by showing that the relationships between Openness, reading, and Gf is also associated with literacy. This finding is in line with the mediation hypothesis from the OFCI model. However, it also supports the idea, that environmental enrichment and the investment of fluid ability work hand in hand to shape Gc. The same holds true for calculating and the influence on numeracy. A higher score in the indicator of Openness goes along with an increase in calculating activities at work and during leisure time. Thus, calculating activities are associated with higher Gf and thereby with higher numeracy.

In summary, differences in activities such as reading and calculating can be the manifestation of Openness, that is associated with cognitive abilities. This supports the ideas behind the OFCI model, especially the Environmental Enrichment Hypothesis. Furthermore, the results of the first two tested models showed that even a very specific activity could foster cognitive ability. This means that the search for new information or learning situations can go beyond only activities that have learning as an agenda (e.g., taking a course at night school). It could be an everyday or work-related activity that makes a difference in the development of cognitive abilities.

Effects on crystallized intelligence in general. In contrast to previous models, Model C was more general. Instead of looking at the association with a specific indicator of Gc, both indicators were used to indicate the construct Gc. The results provide support for the original OFCI model, which is about Gc and not only a specific aspect of Gc. Also, both activities, reading and calculating, were included in this model so that comparisons of the influence of the different mediators were possible. The results from this third model show that neither activity is a more dominant mediator between the indicators of Openness and Gf. The fact that different activities as well as different settings (work vs. leisure) work comparatively well supports another assumption of the OFCI model, which is that environmental enrichment does not have to involve a specific training per se but the general access to new information and situations. Thus, the generalizability of the model is supported.

In addition to the comparison between reading and calculating at work or during leisure time, it is of interest to look more precisely at the activities themselves. By doing so, it becomes clearer what all activities have in common, which is what is specific to the environmentally enriching effect. Results show that for calculating at work and calculating during leisure time, the items that are most representative involve the use of fractions or percentages, thus simple algebra. The use of advanced math is least representative. Thus, the calculating activities that are most likely to enrich the environment and thereby have a positive effect on the development of cognitive abilities are not the challenging tasks of advanced math. Actually, representative items could indicate simple mental computations. With regard to reading, there is a difference between activities done at work and during leisure. In the case of reading at work, the activities that are important include reading emails or notes and articles in newspaper and magazines. Least representative is reading books.

Therefore, a high rate of newness is important rather than dealing with one topic in depth. In the case of reading during leisure time, reading professional journals and manuals or reference literature as well as reading diagrams and graphs is most representative, whereas reading financial statements is least representative. These items could indicate the quickly available and well-edited information about a specific topic that helps people learn more about a special hobby (e.g., improvement of skills). The OFCI model assumes that environmental enrichment is the search for new information and situations to deal with. Thus, our results fit with these ideas. More specifically, reading activities could provide new information, and calculating activities could offer ways to deal with new information.

Limitations

The current study has a number of strengths, including a sample size of more than 5,000 people who were representative of German adults between the ages of 16 and 65 (Rammstedt, 2013; Zabal et al., 2014). Especially, the large and representative sample fosters generalizability to German speaking populations. However, this study also has a number of limitations. One of these is that the PIAAC data include only indicators of intelligence and personality. For example, we used problem solving in technology rich environment (PS-TRE) as an indicator of Gf (fluid intelligence). Indeed, problem solving is a very important part of Gf (Bühner et al., 2008; Greiff et al., 2014), and in this way, it is a very good indicator. However, PS-TRE is not purely measuring Gf, but also Gc. Thus, the association between Gc and Gf could be overestimated in the current study. Furthermore, a broader measure of Gf would be advantageous in order to observe the influence of Openness on Gf. A prerequisite, however, would be for Openness to be measured in an equally broad way as Gf, which was not possible in this study. In the first paper on the OFCI model (Ziegler et al., 2012), the NEO-PI-R (Ostendorf & Angleitner, 2004) was used to measure Openness. Correlational analyses illustrated that the Openness facets differed in their relations to Gf and Gc. In particular, the facets Fantasy, Action, Ideas, and Values seemed to be important. In Study 2 of the same paper, Ziegler and his colleagues looked at the developmental part of the OFCI model. The NEO-FFI (Borkenau & Ostendorf, 1991) was used to measure Openness. Results supported the importance of single Openness facets. Over and above this finding, other authors have shown the diverse relations of Openness facets with ability (Mussel, 2013). The items used in our study to indicate the degree of people's Openness went in the direction of Openness to Ideas. Thus, we used an indicator that focused on the most important facets of Openness in relation to ability. However, the six items indicate only this facet. The same goes for the measurement of crystallized intelligence. The PIAAC data include only numeracy and literacy, which can be used as indicators of Gc. In future research, it might be interesting to investigate which facets of crystallized intelligence are specifically influenced by Openness.

A further limitation is that this study includes only reading and calculating as activities that represent environmental enrichment. The authors of the OFCI (Ziegler et al., 2012) suggested that Openness increases the likelihood of experiencing new learning situations. Reading and calculating are good indicators of activities with learning potential. But there are so many more that could be of interest. Ziegler and his colleagues (2012) gave a number of possible indicators: "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" (p. 180). By knowing about reading and calculating habits, it is not possible to generalize to the whole spectrum of environmentally enriching habits. Therefore, other activities have to be investigated.

A final limitation is the cross-sectional nature of the data. The Environmental Enrichment Hypothesis is part of the developmental perspective of the OFCI model. In a cross-sectional design the direction of influence is ambiguous. We want to support the Environmental Enrichment Hypotheses, which is about an influence from Openness to cognitive abilities by activities. However, the other direction is equally possible. So, people with higher cognitive abilities could increase their Openness over time, because of feeling success and enjoyment in learning situations. This is what a further hypothesis of the OFCI model assumes. Like the Environmental Enrichment Hypothesis also the Environmental Success Hypothesis could be mediated by activities in job and during leisure time. So, people search for learning situation because of a positive feeling like success. Thus, both possible directions support the OFCI model and our idea of mediation by activities.

In the perspective of Environmental Enrichment Hypothesis, Openness at one time is assumed to influence Gf, so development should be measured at a later time point. To determine whether Gc is influenced directly by Openness and also indirectly via Gf, an additional time point is needed. In this paper, because the environmental enrichment hypothesis was not only assumed but was also defined more precisely, we added a variable to the model to mediate the path from Openness to Gf. By adding this mediating variable, one additional time point would be necessary to test the complete indirect path. In conclusion, a design with at least four time points would be needed. In this paper, we used PIAAC data that did not dispose of this number of occasions. Therefore, we used the present data to compute cross-sectional analyses of the Environmental Enrichment Hypothesis. However, a longitudinal design is needed and should be implemented in further studies.

Concluding Remarks

In our study, not only were we able to support the OFCI model, but we also looked more precisely at possible activities underlying environmental enrichment and asked the question of what exactly it is that people do to enrich their environment. The study supports, that people with a higher level of Openness are more likely to search for more learning opportunities; this fosters their Gf and ultimately affects Gc. These learning opportunities can be found in daily life and in work activities such that reading activities in particular serve as a source for new information, and calculating activities at work and during leisure time indicate new situations to deal with.

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