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Spearman's law of diminishing returns. A meta-analysis

Diego Blum*, Heinz Holling

Westfälische Wilhelms-Universität Münster, Fliednerstraße 21, 48149 Münster, Germany

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ABSTRACT

The cognitive ability differentiation hypothesis, which is also termed Spearman's Law of Diminishing Returns, proposes that cognitive ability tests are less correlated and less *g* loaded in higher ability populations. In addition, the age differentiation hypothesis proposes that the structure of cognitive ability varies across respondent age. To clarify the literature regarding these expectations, 106 articles containing 408 studies, which were published over a 100-year time span, were analyzed to evaluate the empirical basis for ability as well as age differentiation hypotheses. Meta-analyses provide support for both hypotheses and related expectations. Results demonstrate that the mean correlation and *g* loadings of cognitive ability tests decrease with increasing ability, yet increase with respondent age. Moreover, these effects have been nearly constant throughout the century of analyzed data. These results are important because we cannot assume an invariant cognitive structure for different ability and age levels. Implications for practice as well as drawbacks are further discussed.

1. Introduction

1.1. Theoretical background

For more than a century, the psychometric tradition underlined the importance of a structural organization of abilities following a hierarchical order. According to the theory, hierarchical abilities can be placed in vertical direction from the most general at the head, until the most specialized at the bottom, where upper levels have an impact on lower levels (Burt, 1949; Carroll, 2003; Spearman, 1904; Thomson, 1919). Furthermore, this hierarchical theory has been used as a basis for the development of more specific theories, all of them giving particular importance to the role and properties of higher-order abilities. Examples are the broad constructs named as Fluid and Crystallized Ability by Cattell (1943) and Horn (1976), Thurstone's (1938) Primary Mental Abilities, the Berlin Intelligence Structure Model (BIS; Jäger, 1982, 1984), the three levels of ability proposed by Carroll (2003), and Spearman's (1904, 1927) General Intelligence or *g*. The latter is a single higher-order composite that is said to generate a positive manifold among abilities of different kinds.

Spearman demonstrated the existence of a *g* factor through positive correlations among the scores of individuals in several maximum-performance tests. Furthermore, he presented evidence suggesting that the amount of this general composite decreases as a function of ability (1927), i.e., the higher the ability, the lower the correlations among the tests will be. This evidence is based on research showing a tendency of reduced inter-test correlation coefficients for groups of higher-skilled individuals compared to those lower-skilled (i.e., normal vs. defective children, older vs. younger children, and adults vs. children).

Although these results suggest that an inverse relationship between the *g* saturation and ability is present, Spearman did not specify the type of relation (linear, curvilinear, logarithmic, etc.). He also did not constrain his study to any age or intelligence range in particular. Hence, the evidenced effect is a broad and unspecific interpretation of a few results. Nevertheless, he explained the phenomenon by stating that these higher-skilled groups comprised a higher amount of mental "energy" (p. 219), and that, as a consequence, ability was being less benefited from further increments of it. He considered this to be analogous to a fundamental principle of economics called the Law of Diminishing Returns.

This law states that, if the amount of input of a production process continuously increases and all of the other production factors stay constant, the rate of growth of the output will eventually decrease; this means that returns are diminished at a certain level as a consequence of expanding the volume of input. Thus, from a psychometric point of view, indicators of higher ability, such as an elevated *IQ* or increased age, could be accompanied with abilities being less dependent among each other and, therefore, less saturated with *g*.

This relationship was further explained as an increase of cognitive specialization, often known as the differentiation hypothesis. It states that factor patterns of intelligence are more differentiated when a personal condition, like being higher-skilled or older, is met (Reinert, 1970). With respect to ability, the differentiation hypothesis implies that factor structures are more differentiated for high-ability than for low-ability individuals, also called the ability-differentiation hypothesis

* Corresponding author.
E-mail addresses: blumworx@gmail.com (D. Blum), holling@uni-muenster.de (H. Holling).

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by Reinert, Baltes, and Schmidt (1965). With respect to age, it implies that "abstract or symbolic intelligence changes in its organization as age increases from a fairly unified and general ability to a loosely organized group of abilities or factors" (Garret, 1946, p. 373). This was called the age-differentiation hypothesis by Anastasi (1958), with much research attempting to describe how factor structures of intelligence develop as a function of age (Reinert, 1970). A comparable theory of age differentiation extended to the entire life span states, however, that while this phenomenon occurs from childhood until early maturity, the opposite effect (i.e., the increase of the importance of the general ability composite) is expected from early to late maturity, thus suggesting the existence of a U-shaped relationship (Balinsky, 1941). On the contrary, Spearman (1927) did not seem to consider the entire life span; he only went as far as to compare adults with children, and no suggestion of a U-shaped effect was accomplished by him. Finally, an intersection point can be found between these two hypotheses because an earlier age level is usually marked by a lower ability level (Reinert, 1970).

1.2. Current state of knowledge

The interest in finding evidence about Spearman's expectations as well as the differentiation effect kept psychometricians busy throughout practically 100 years, and, according to Fogarty and Stankov (1995), researchers paid more attention to this topic during the last decades of the XX century. However, proof about such an effect, as well as against it, creates a contradictory state of knowledge (Hartmann & Nyborg, 2006; Reinert, 1970). As an example of ability differentiation, Detterman and Daniel (1989) revealed that individuals with low *IQ* comprise higher correlations among *IQ* tests than individuals with high *IQ*. As opposed to this finding, Amelang and Langer (1968) divided their sample in two groups distanced by 12 to 13 *IQ* points who responded to a number of ability tests, and the difference between the first unrotated eigenvalues of the two data sets was found to be non-significant by Hartmann and Nyborg (2006).

Regarding the age differentiation, Hertzog and Bleckley (2001) studied the performance of three groups of individuals with respect to a battery of cognitive tests. One of the groups consisted of undergraduate students, and the other two comprised age ranges of 43–62 and 63–78. The general tendency was that both test and factor intercorrelations were higher for older groups than for younger ones. On the contrary, Escorial, Juan-Espinosa, García, Rebollo, and Colom (2003) found practically no change regarding the percentage of variance accounted for by the first unrotated principal component between groups with a respective age range of 16–24 and 35–54 that responded to a set of ability measures.

It is important to notice that nearly all of the existing studies related to differentiation arrive at results which can be deemed as partialized, given that they more or less depend on the selected sample, the chosen test battery, the place of conduction, among other variables. Thus, a reasonable doubt about the possibility to be able to compare results among publications is present. In fact, Molenaar, Dolan, Wicherts, and van der Maas (2010) mention some interesting critiques to current research reporting correlation matrices among subtests, which can be summarized as follows:

- Most research methods are ad hoc and lack of explicit framework. Therefore, they have not enough quality.
- Creating subgroups, each with different predictor levels, and studying the *g* differences among them can be problematic because the factor structure may be different for the whole population than it is for each subgroup, which could lead to the distortion of the subtest correlations within subgroups as well.
- To solve the latter issue, some other researchers created subgroups based on the latent variable (i.e., second-order factor) in order to distort the factor structure of the subgroups in a lower degree. The problem is that the structure is not preserved with many types of factor scores because "the covariances among the common factors based on the calculated factor scores are not equal to the covariances as estimated in fitting the factor model" (p. 613).
- Researchers are generally not unanimous about which specific *g* measure to use.

To our knowledge, only one recent attempt has been made by Hartmann and Nyborg (2006) to perform a detailed review of the existing literature pertaining the differentiation effect with the purpose of establishing a comprehensive understanding of it. By following some of Reinert's (1970) previous short review, Hartmann and Nyborg accomplished an enormous summary and categorization of empirical research from 1923 until 2004. They showed how several measures of the *g* saturation, such as the mean correlation among ability tests, the first unrotated eigenvalue or its total explained variance, change depending on ability or age, in accordance with previous research. They assessed statistical differences regarding the mean correlation between groups differing on ability or age, and for that purpose they used the *t*-test on Fisher's *Z*-transformed correlations in consonance with Lynn and Cooper's (1993, 1994) approach. They also scored the selected studies with a maximum of 4 quality points depending on whether researchers published one of the expected *g* measures such as the average intercorrelation (1 point), controlled or manipulated ability (1 point) or age (1 point), and whether they controlled the *SD* of ability (1 point).

According to Hartmann and Nyborg's results regarding ability effects, out of the 9 ability-related studies considered by them to be of highest relevance (i.e., those within the range of 3½–4 quality points), 3 show a tendency of decreasing *g* saturation as a function of ability, only significant in one case, other five show no relation or a very modest relation between the variables, and the remaining study reveals an increasing effect. After recalculating scores by giving also one point to studies not controlling for age, Hartmann and Nyborg were left with 18 papers in the subgroup, 10 out of which show a decreasing effect, six of them being significant. Hartmann and Nyborg concluded that there seems to be a moderate support for a small effect of ability on the *g* saturation.

With respect to studies of the impact of age on the *g* composite, most research reveals a *g*-saturation increase in later life, and almost 50% of the studies "point in the direction of a non-significant tendency towards a U-curvilinear relationship between *g* saturation and age, with the minimum *g* saturation from ages 18-34" (p. 110). This seems to confirm the extended theory of age differentiation already described (Balinsky, 1941). Another 25% of all studies does not reveal a relation whatsoever between both variables, and 15 to 20% of the remaining literature shows an inverted U-shaped relation where the *g* saturation is the highest within the age period 10–14. Furthermore, according to a subsample of age-related studies which were given 3½–4 quality points, Hartmann and Nyborg found their results to be even more contradictory than the ones of the broader sample. Therefore, it was their point of view that outcomes are not supportive of the age differentiation effect.

Hartmann and Nyborg argued that the effect of age on the *g* saturation is perhaps mediated by the effect of ability. In fact, Spearman (1927) did not ever mention that *g* could be a function of age. He only gave examples where groups of younger and older individuals were being compared with respect to *g*, given that the ability level was expected to be different across these groups as well. Moreover, ability is known to drastically change along the earlier years of life, and then the relation between ability and age diminishes (Kalveram, 1965; Merz & Kalveram, 1965). Finally, Reinert et al. (1965) found that, when ability is kept constant, no effect of age on the *g* saturation is present. If results supporting a U-shaped relationship between age and *g* loadings are considered, this relation approximately fits with an inverted U-shaped relation between age and ability, where ability is maximal at middle ages (Hartmann & Nyborg, 2006).

All in all, according to Hartmann and Nyborg's review, 10 out of the