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Decomposing the functional relationship between speed of information processing in the Hick paradigm and mental ability: A fixed-links modeling approach

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ABSTRACT

In his scholarly work, Bob Stelmack insistently reminded that response times represent an index of various cognitive processes that are unlikely to be functionally related to individual differences in mental ability to the same extent. Here, we introduce a fixed-links modeling approach to cope with this so-called impurity problem inherent in virtually all reaction time (RT) measures used within the mental speed approach to intelligence. For this purpose, we decomposed the variance of individual differences in RT obtained with the Hick RT paradigm into an experimental latent variable (LV) representing individual differences in RT associated with the systematically increased number of response alternatives in the Hick task, and a non-experimental LV representing individual differences in RT unrelated to this experimental manipulation. While the experimental LV explained a significant portion of 11.6% of variance in mental ability, the non-experimental LV accounted for only 2.6%. This outcome clearly indicates that, with the Hick RT paradigm, the functional relationship between speed of information processing and mental ability is primarily caused by individual differences in decision latency as a function of the experimentally increased number of response alternatives. Fixed-links modeling proved to be a highly suitable procedure to deal with the impurity problem.

1. Introduction

During the past four decades the so-called mental speed approach to human intelligence has provided a large body of scientific evidence for a positive relationship between psychometric intelligence and speed of information processing in elementary cognitive tasks (ECTs). Even though the faster speed of information processing on ECTs for higher than lower ability individuals can be considered an established fact (Jensen, 1998a, 2006; Sheppard & Vernon, 2008), our understanding of the nature of the neural processes that underlie this co-variation is largely unknown (Stelmack, 2001).

Within the mental speed approach, one of the oldest and most frequently used ECTs is the Hick paradigm. It is based on Hick's (1952) discovery of a linear increase in reaction time (RT) with the binary logarithm of the number of equally likely response alternatives in a visual RT task. In the Hick paradigm, the number of response alternatives and, as a consequence, the number of required binary decisions is increased systematically across several task conditions. In the easiest condition (i.e., simple RT) there are no response alternatives and, thus, no decision is required. In the more complex choice RT conditions, the number of response alternatives is systematically increased so that an increasing number of binary decisions are required for a proper response.

As early as 1964, Roth related the slope parameter, reflecting the linear increase in RT across the different Hick task conditions, to psychometric intelligence. He found a negative relationship between the slope parameter and intelligence. This finding did not only indicate faster RTs for more intelligent compared to less intelligent individuals but also that this difference increased with increasing task difficulty. Since then, numerous studies confirmed a consistent, albeit quite moderate, negative relationship between Hick RT measures and psychometric intelligence (for reviews see Jensen, 1998a, 2006; Sheppard & Vernon, 2008).

Although Bob Stelmack's research does not particularly focus on the Hick RT paradigm, his scientific work on individual differences in speed of information processing addresses crucial and fundamental questions that also apply to the Hick task. According to Bob's view, response times represent an index of various cognitive processes and, for instance, include time relating to stimulus processing, decision making, and response organization (e.g., Doucet & Stelmack, 1997, 2000; Stelmack, 2001; Stelmack, Houlihan, & McGarry-Roberts, 1993). At the same time, however, he gives rise to particular concern that all these different processing stages are unlikely to be functionally related to individual differences in mental ability to the same extent (cf. Doucet &

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Stelmack, 2000). Based on this central idea, response times obtained with the Hick RT paradigm can be roughly divided into two major components referred to as *decision latency* and *residual latency* (see also Luce, 1986). The decision latency represents the time required for the execution of the mental operations directly related to the experimentally varied number of response alternatives, whereas the residual latency reflects the time needed for all other processes independent of the experimental manipulation such as basal stimulus processing and response execution. Thus, it remains unclear what source of variance (i.e., which of these two components) underlies the observed functional relationship between RT and mental ability observed with the Hick task.

Three decades ago, Jensen (1987) put forward the idea to use the slope parameter and the intercept of an individuals' regression line across the different levels of task difficulty to solve this so-called impurity problem. While he considered the intercept to reflect 'constant' processes not affected by experimentally increased task difficulty (i.e., residual latency), the individual slope parameter of the RT function across the different task conditions was assumed a valid indicator of the time needed for the required binary decisions and, thus, reflecting decision latency.

Unfortunately, however, this methodological approach suffered from typically small and nonsignificant correlations observed between the slope parameter and psychometric intelligence. A very detailed account of why the slope parameter does not represent a good measure of individual differences is provided by Jensen (1998b, 2006). To put it briefly, first, reliability of the slope parameter is rather low. Secondly, there is an inherent suppression effect caused by negative correlations between shared errors of measurement of slope and intercept. That is, if one of these two parameters is correlated with psychometric intelligence, the other parameter acts as a suppressor variable on that correlation resulting in an underestimated correlational relationship. Due to these shortcomings, the slope parameter has been largely discarded as a mental speed measure (cf. Sheppard & Vernon, 2008).

More recently, Schweizer (2006, 2008) introduced fixed-links modeling (FLM) as an alternative methodological approach to cope with the impurity problem. FLM is a kind of structural equation modeling and represents a special form of confirmatory factor analysis (CFA) for experimental repeated-measurement designs. As an advantage over manifest approaches, FLM exclusively considers the true variance shared by several manifest variables as represented by latent variables. Hence, shared errors of measurement are not comprised and, as a consequence, suppression effects do not bias the functional relationship under investigation.

Similar to Jensen's slope-intercept approach, most FLM studies propose to decompose variance into two components: an experimental latent variable (LV), representing individual differences in processes directly affected by the different levels of the experimental manipulation, and a non-experimental LV, representing individual differences unrelated to the experimental manipulation (Schweizer, 2007, 2008). In order to extract these two LVs from the same set of manifest variables, fixation of factor loadings is required. The factor loadings of the experimental LV are fixed in accordance to the theoretically expected trajectory caused by the experimental manipulation (e.g., an increasing trajectory across task conditions), whereas all factor loadings of the non-experimental LV are fixed to the same value indicating consistency across treatment levels. Given that all factor loadings are fixed and not estimated, variance of the LVs is set free and needs to reach statistical significance in order to be interpreted as psychologically meaningful.

Based on these considerations, the aim of the present study was to yield a deeper understanding of the functional relationship between RTs obtained with the Hick paradigm and mental ability by decomposing the variance of individual differences in RT. More precisely, in a first step, we aimed at the identification of two LVs: one LV representing individual differences in the time required for the execution of the mental operations directly related to the experimentally varied number of response alternatives, and another LV representing individual differences in RT unrelated to the experimental manipulation. Accordingly, our working hypothesis was that it should be possible to statistically dissociate variance in RT caused by the systematic experimental variation of number of response alternatives in the Hick task from residual variance and, thus, to solve the impurity problem. As this assumption held, in a next step, we analyzed the portions of variance in mental ability accounted for by the experimental and the non-experimental LV, respectively. In line with Roth's (1964) and Jensen's (1987, 2006) view, we assumed the experimental LV to predict a larger portion of variance in mental ability than the non-experimental LV.

2. Method

2.1. Participants

The participants were 70 male and 80 female volunteers from a convenience sample ranging in age from 17 to 32 years (mean and standard deviation of age: 22.0 ± 3.1 years). All participants had normal or corrected-to-normal vision and gave their written informed consent. The study was approved by the local ethics committee.

2.2. Measures

For measurement of psychometric intelligence, a short version of the Berlin Intelligence Structure (BIS) test (Jäger, Süss, & Beauducel, 1997) was used. This short version consisted of 18 subtests to measure Processing Capacity, Processing Speed, and Memory as three major facets of psychometric intelligence. Each facet was assessed by two figural, two numerical, and two verbal subtests.

For statistical analyses at the level of manifest variables, a BIS full-scale score (i.e., the number of correctly solved items across all subtests) as a measure of general mental ability was computed for each participant (cf., Jäger et al., 1997). For modeling a *g* factor of intelligence for analyses at the level of latent variables, the raw scores of each subtest were *z*-standardized. Then, in a next step, a LV, representing the *g* factor of intelligence, was derived from the aggregated mean *z*-scores of the three facets of intelligence (cf. Stauffer, Troche, Schweizer, & Rammsayer, 2014). In a previous pilot study, Wicki (2014) showed satisfactory test-retest reliability ($r_{tt} = 0.79$) for this *g* factor of intelligence derived from Processing Capacity, Processing Speed, and Memory measured with the very same subtests as in the present study.

2.3. Procedure

A Hick RT task was used similar to the one proposed by Rammsayer and Brandler (2007). In the 0-bit condition (H0; no-choice or simple RT), each trial started with the presentation of a rectangle in the center of the monitor screen. After a foreperiod varying randomly between 1000 and 2000 ms, the imperative stimulus ("+") was presented in the center of the rectangle. The 1-bit condition (H1; two-choice RT) was identical to the 0-bit condition, except that two rectangles were presented arranged in a row. The imperative stimulus was randomly presented in each of the two rectangles in 50% of the trials. In the 2-bit condition (H2; four-choice RT), four rectangles arranged in two rows were displayed on the monitor screen. The imperative stimulus was presented randomly in each of the four rectangles in 25% of the trials.

Participants were instructed to respond as quickly as possible to the imperative stimulus by pressing the response key corresponding to the rectangle with the imperative stimulus but to avoid response errors. After an intertrial interval of 1100 ms, the next trial started. Incorrect responses were followed by a 200-ms tone. As suggested by Jensen (2006), task conditions were presented in ascending order. Each condition consisted of 32 trials preceded by 10 practice trials. As performance measure, mean RTs of correct trials were computed for all three task conditions.