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A process-based account of the speed-ability relationship for the Posner Task

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Abstract

A process-based approach is selected for studying the relationship between intelligence and the speed of information processing on the basis of the Posner Task. By applying meta-analytic methods, several studies involving this letter-matching task were used for gaining a large data set. Within the Posner Task, participants had to react to stimuli according to two different instructions. The first instruction required mainly perceptual processes, whereas the second involved mostly memory processes. Using a model with fixed links between manifest and latent variables, and a step-wise procedure to determine parameters, enabled us to study the influences these processes have on intelligence individually. The results of our study show a much stronger influence of memory processes than of perceptual processes. Also our study illustrates the advantages a fixed-links model can have in studying separate influences of processes, as opposed to a standard structural equation model.

Key words: Posner Task; fixed-links model; elementary cognitive tasks; intelligence

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The connection between intelligence and memory-performance has been studied on numerous occasions, and the results have shown a consistent correlation between intelligence and reaction time, respectively speed of information processing (Vernon & Kantor, 1986; Vernon & Jensen, 1984). Individuals with higher intelligence usually show faster and less variable reaction times and the correlation between the two even increases when the cognitive tasks involved in the testing are more complex (Miller & Vernon, 1992).

It is very useful to turn to processing models in order to study the connection between intelligence and memory. These models represent assumed mechanisms that regulate storage of and access to information. The quality of those processes is a vital component in determining the degree of accessibility of stored information and, therefore, decides how quickly it can be made available (Renkl & Schweizer, 2000). One important model that should be named in this context has been introduced by Craik and Lockhard (1972). In their *levels-of-processing* model, they distinguish between separate stages for sensory, working and long-term memory. According to their model, stimulus information is being addressed at multiple levels simultaneously and can reach different levels of processing. "Deep" processing means identifying the semantic content, connecting it to the stimulus, and by creating links for embedding it into already present information. A second process, which only takes place at the surface, stores information based on its perceptual features. Therefore its content cannot be retrieved via meaning, which usually impairs the speed and accuracy with which the required information can be accessed.

A different group of models that can also be considered processing models are called *production systems.* They were introduced by Newell and Simon (1972). A production system (or just production) is a collection of if-then rules. These rules are used to store and access information, and are also used in processing intelligence tasks (Renkl & Schweizer, 2000).

One processing model that focuses specifically on individual differences in performance concerning memory tasks has been introduced by Hunt (1978). Hunt distinguishes between two processes, which play a role in the storage and access of memories. According to Hunt the first process is based on knowledge. It is necessary to acquire information in order to learn the concepts of language and the ability to use it. Also Hunt points out, that skills like problem-solving have to be acquired through explicit instructions. Obviously, a vaster level of suitable knowledge improves a person's chance to solve a larger number of problems.

Hunt also names a second process that can influence differences in performance. This process is information-free and Hunt describes it as *mechanistic.* This mechanistic process targets the physical representation of the stimulus and not the information associated with the stimulus (Hunt, 1978). This happens unconsciously as part of information-processing, and according to Hunt, influences performance on verbal tasks.

An analogy to a library will help illustrate the meaning of those processes. In order to function effectively, a library has to provide its users with overviews of the books that are stored. It has to enable them, to find said books and to return them to their correct place after use. It also requires the ability to grow, to add and correctly store new information (Renkl & Schweizer, 2000). A library that cannot guarantee that these processes are running smoothly isn't sufficiently equipped to satisfy its visitors, which inevitably will result in negative consequences. The same statement can be made for memory if access to information is impaired.

By developing different parameters that play a role in information-processing, Hunt identified indicators that can explain differences in individual performance. One test that is particularly suitable for determining the speed of long-term memory retrieval was developed by Posner (Posner, Boies, Eichelmann & Taylor, 1969; Posner & Mitchell, 1967). In this letter-matching task, the participants are shown two letters that are either physically the same (e.g. 'AA'), physically different but semantically the same (e.g. 'Aa') or physically and semantically different (e.g. 'Ab'). This task usually includes two treatment levels: In a first treatment level the participants are asked to judge whether the stimuli are physically identical (PI-Test). In a second treatment level they have to judge whether the stimuli are semantically identical (name identity or NI-Test). In the first test the participants have to make a decision solely based on visual discrimination whereas the second test requires them to access highly overlearned information stored in long-term memory (i.e. letters of the alphabet). The difference in the reaction-time for the two treatment levels was, therefore, considered as a measure of the speed of retrieval of long-term memory contents (Hunt, 1980).

In earlier studies, Hunt investigated the relationship between parameters of the Posner Task and intelligence. He examined groups with varying degrees of intellectual ability, and found the smaller NI-PI differences for groups of high verbal ability (Neubauer, Riemann, Mayer, & Angleiter, 1997). This would indicate that verbally efficient subjects are capable of quicker long-term memory retrieval.

Lansman, Donaldson, Hunt and Yantis (1982) conducted a study in which they examined the information processing correlates of college students (Hunt, 1980). They computed correlations between the reaction times for the NI and the PI conditions, the NI-PI difference and several tests measuring fluid and crystallized intelligence according to Cattell (1971). They found a moderate (0.29) loading on Cattels crystallized (Gc) factor for the NI-PI measure. Other studies produced similar results for investigating the relationship with intelligence (Warren, 1978). There were correlations of about -0.30 which have been found for the NI-PI measures and verbal aptitude scores. Warren (1978) found a correlation of -0.34 for NI-PI and verbal scores of the Wechsler Intelligence Scale for Children (Wechsler, 1949) in grade school children. Studies on extreme groups have shown that smaller NI-PI measures are associated with higher verbal aptitude, and lower aptitude scores with bigger differences.

Neubauer (1995) surveyed several studies using a correlational approach. For a total of 1,064 participants, Neubauer found a correlation of -0.23 for the mean reaction time of the PI treatment level. A somewhat higher negative correlation (-0.33) was found for the mean reaction time in the NI treatment level. The NI-PI difference also correlated (-0.27) negatively with intelligence. However, according to Neubauer, these results are to be treated with caution. Their generalizability is to be questioned because different tests were used to measure intelligence.

The modeling of cognitive processes

When the focus is on latent concepts and sets of measures are available, structural equation models (SEM) are often used in order to study, test or estimate the relationships between said concepts. These concepts are considered as latent variables that are estimated within the model on the basis of several manifest variables. Typically, in SEM the different manifest variables are considered as mostly equivalent (Schweizer, 2006). Herein lays the strength of

SEM, enabling researchers to estimate relationships between latent variables that can't be targeted directly. In certain cases, however, problems can arise when using standard SEM (Jöreskog, 1973; Keesling, 1972; Wiley, 1973). In some such cases systematic differences were found between the variances of manifest variables, for example by Jensen and Munro (1979) while studying reaction times. Addressing these problems requires a specific type of SEM that includes constrained models of measurement. In standard SEM the loadings that link manifest and latent variables are free to be estimated. Models of measurement that include such links do well if the data require more or less equivalent loadings. However, they are likely to fail if specific patterns of loadings (increasing, decreasing loadings) would be required.

In order to address this problem, a specific type of models denoted fixed-links models can be used. The solution to the problem by means of fixed-links models is the constraint of loadings according to systematic patterns. Such models are especially well suited for investigating repeated-measures data (Schweizer, 2008). The repeated-measures data of cognitive research frequently show considerable differences between the variances of measures because of the experimental treatment. These differences in variance and covariance are due to different contributions of cognitive processes. The constraints of loadings can be selected to represent such processes and applied for predicting differences in variance accordingly. For example, it proved useful to distinguish between main cognitive processes (e.g. storage processes) and subsidiary processes (e.g. motor processes) in investigating reaction times (Schweizer, 2009a). Furthermore, specific effects, as for example the attentional blink (Troche, Schweizer, & Rammsayer, in press), can be represented. Accordingly, fixed-links models provide the opportunity for the modelling of cognitive processes. Theory-driven explanations can provide the outset for fixing links between manifest and latent variables. As a consequence, there is the opportunity of resuming the investigation of old research questions, which have so far been treated at the manifest level with limited means only.

Fixed-links models for investigating the Posner Task

The considerations associated with the Posner Task are based on the assumption that there are distinguishable perceptual and memory processes or sets of such processes, which are necessary to perform cognitive operations according to task demands (Hunt, 1980). Furthermore, it is assumed that either individual processes or sets of processes can be stimulated by different experimental treatments. With respect to the Posner Task it is assumed that the physical identity treatment (PI) mainly simulates perceptual processes including the processes for comparing stimuli on the basis of the physical properties of these stimuli in addition to some other processes. In excess of these processes the content identity treatment (NI) is assumed to stimulate access to information stored in long-term memory so that the comparison can be performed on the basis of semantic properties.

Fixed-links models enable the separation of types of processes, just as it is prepared by the treatment levels, and in the consequence, they allow the researcher to investigate the characteristics of such types. For example, the whole of processes may be subdivided into main processes and subsidiary processes (Schweizer, 2009a). A similar subdivision is feasible for the processes stimulated by the Posner Task. The reasoning concerning this Task introduced by Hunt (1980) and others suggests a subdivision of processes into mainly perceptual processes and mainly memory processes so that it becomes possible to investigate the characteristics of memory processes independently. Although the reasoning by Hunt concentrates on memory processes, the reaction time achieved for the content identity treatment does not represent memory processes solely so that it was necessary to compute difference scores formerly. However, this approach is questionable since difference scores are known to show a low reliability. Furthermore, they led to disappointing results (Neubauer, 1997).

The Posner Task requires the construction of a fixed-links model with two latent variables for representing the sets of processes giving rise to the reaction times stimulated by the two treatment levels and also one latent variable for representing intelligence that serves as criterion in the investigation. One of the two latent variables should represent all those processes that can be assumed to contribute to performance according to both treatments. The reaction times as manifest variables should show equal-sized loadings on this latent variable since the same type of stimuli is used in both treatments so that a high degree of similarity in processing can be assumed. The other latent variable should represent the cognitive processes that are additionally necessary for meeting the demands of the content identity treatment. Because it usually proves useful to constrain the loadings on different latent variables according to the various constituents of the polynomial, the constraints should show a linear increase. In Figure 1 the increase is represented by α. Furthermore, the models must include an intelligence test score that loads on the latent variable representing intelligence. The basic structure according to these considerations is given by Figure 1.

In this model the increase represented by α is a crucial property. A low value of α indicates that not only the reaction time for content identity includes memory processes but also the reaction time for physical identity. In contrast, α should be very large if the contribution of memory processes is virtually restricted to the reaction time for content identity. Since there is the possibility of varying the size of α, the model provides the possibility to check whether the reaction time for physical identity also includes a contribution of memory processes. Unfortunately, the model includes more parameters than there are numbers that pro-

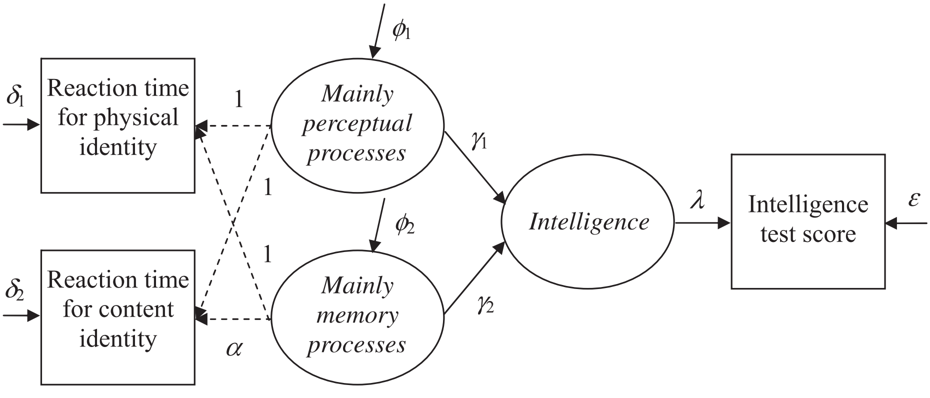

Figure 1:
Basic structure of the model for representing the reaction times of the Posner task and their relationship to intelligence.

vide the basis for the statistical investigation. In order to overcome this shortcoming and to avoid an influence of the constraints on the estimation of the error components, it is reasonable to assume equality of error components ($\delta_1 = \delta_2$). However, even this assumption does not guarantee a minimum of one degree of freedom.

Since the investigation of the relationship between the two types of processes and intelligence is the main aim of this paper, the research work must concentrate on the achievement of valid estimates of γ_1 and γ_2 of the model. Since such estimates can not be achieved directly, it is necessary to find estimates for ϕ_1 and ϕ_2 in an intermediary step. This goal can be reached by investigating the dependency of the estimates on modifications of the constraint α.

Method

Participants

The data used in the study were assembled by means of meta-analytical techniques in order to achieve a very large sample. Four separate studies including a total of 535 participants (Levine, Preddy, & Thorndike, 1987; Miller & Vernon, 1992; Vernon & Jensen, 1984; Vernon & Kantor, 1986) provided the outset for the achievement of an overall covariance matrix. The covariance matrices of the individual studies were merged in considering the different sample sizes. The intelligence test statistics were standardized before merging in order to eliminate differences due to different intelligence tests. A detailed description of the overall sample is unfortunately not possible because information concerning gender and age was incomplete in some of the studies.

Measures

Different intelligence tests were used to measure the level of intellectual ability. Those were the Cognitive Abilities Test (CogAT) (see Levine, Preddy & Thorndike, 1986), the Multidimensional Aptitude Battery (MAB; Jackson, 1983) and the Armed Services Vocational Aptitude Battery (ASVAB) (see Vernon & Jensen, 1984). All these tests measure fluid intelligence. By means of standardization it was made sure that the different empirical characteristics of these intelligence tests had no effect on the results.

In all the studies access to the contents of long-term memory was measured by means of Posner's letter-matching task (Posner, Boies, Eichelmann & Taylor, 1969; Posner & Mitchell, 1967) known as the Posner Task. Participants were simultaneously shown a pair of letters on a computer-monitor. It was their task to decide as fast as possible, whether the two letters were "the same" or "different" and to react accordingly by pressing one of two response buttons. There were two experimental treatments. In the first treatment the participants were asked to judge the physical identity (PI) of the two letters (e.g. 'AA'). In the second treatment they had to judge name-identity (NI) (e.g. 'Aa'). Each study included several trials according to each one of the two treatments. The number of trials given for each treatment ranged from 18 to 30. The outcomes were accuracy and response time. However, data analysis concentrates on response time.

Statistical investigation

The statistical investigation was especially demanding since there were only two performance measures, which served as manifest variables. These manifest variables were to be analysed in such a way that they could be taken as manifestations of two latent variables. A further complication of the situation resulted from the uncertainty concerning α. Because of all these complications a stepwise procedure was selected for achieving the final result.

In the first step, a restricted model of measurement was selected for representing performance according to the Posner Task. This model included two manifest and two latent variables. Part A of Figure 2 gives a graphical illustration of this model.

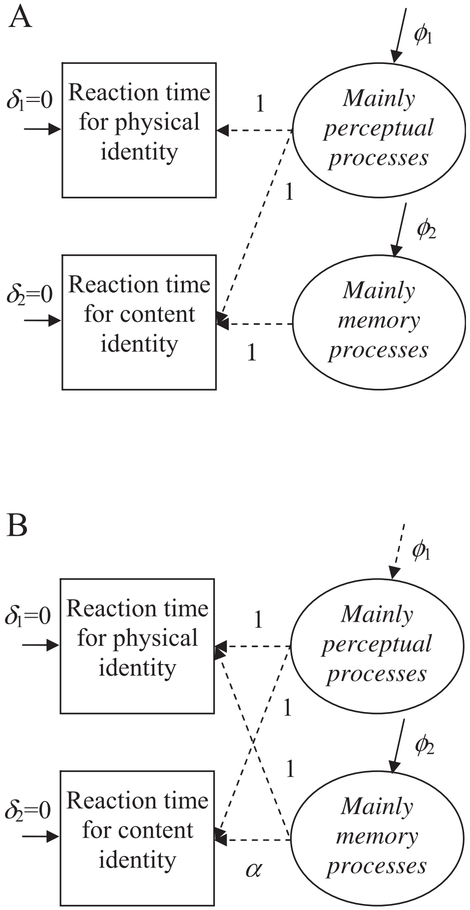

Figure 2:
Basic model of measurement for the Posner Task (A) and complete model of measurement for the Posner Task (B)

This model was quite restrictive because it assumed that the error components were zero and that the latent variable representing "mainly memory processes" received one loading only. It required the estimation of two parameters (ϕ_1 and ϕ_2) only. This model served the achievement of an estimate of the variance of the first latent variable (ϕ_1). The other estimate of variance was not considered as appropriate because there was only one loading.

In the second step a complete model of measurement was investigated in order to achieve estimates of α and ϕ_2. For being able to achieve these estimates, the model of measurement of the first step was modified a bit. First, the variance of the latent variable representing "mainly perceptual processes" was constrained according to the variance estimate obtained in the first step. Second, the reaction time for physical identity that served as the first manifest variable was allowed to load on the latent variable representing "mainly memory processes". However, this loading was fixed to one in order to be able to vary the size of the other loading on this latent variable. Third, the loading of the reaction time for content identity that served as second manifest variable on the latent variable representing "mainly memory processes" was converted into an adjustable constraint. An illustration of this model is given by part B of Figure 2. In the search for the most appropriate values for α and ϕ_2 preference was given to α. It was considered as most important that an appropriate relationship of the two loadings (constraints) was established. Therefore, a specific procedure was selected for the achievements of estimates: a set of numbers selected from a reasonable-sized range and with a reasonable spacing was complied; these numbers were consecutively inserted as α into the model for investigating model fit, i. e. α was adjusted consecutively; in the end the α leading to the best model fit was determined.

The problem of this procedure of determining α is that the variance of the second latent variables (ϕ_2) becomes smaller and smaller since there is dependency of the sizes of variance and corresponding loadings respectively constraints. The standardization of loadings can help to achieve variances of a reasonable size. The following criterion was proposed for standardization (Schweizer, 2006, 2009b):

$$p\boldsymbol{I} = \operatorname{diag}\left(\boldsymbol{\Lambda}'\boldsymbol{\Lambda}\right)$$

where Λ is the $p \times q$ matrix of standardized loadings respectively constraints, $\mathbf{I}$ the $q \times q$ identity matrix and p the number of manifest variables. This criterion was applied to the constraints of the complete model in order to achieve a variance with a reasonable size.

In the third step the restriction of error components to zero was removed since it was unreasonable to assume perfect reliability. The error components were restricted to values that represented high reliability but not perfect reliability. Furthermore, the error components of the reaction times were restricted in such a way that completely standardized values corresponded.

In the fourth step the model of measurement was transformed into a complete structural equation model by adding an endogenous latent variable representing fluid intelligence and an intelligence test score serving as manifest variable.

Results

The search for parameter estimates for the model of measurement

The first step in the search for parameter estimates, as it is described in the method section, led to $\phi_1 = 0.05$. Therefore, ϕ_1 was constrained to 0.05 for the investigations according to the second step in the search for α and the estimate of the second variance.

The second step of the search concentrated on α. At first, a list of numbers, which potentially might provide a good representation of the relationship between the two constraints, was compiled. This list of numbers is included in the first column of Table 1.

The numbers of this column gave rise to relationships of constraints ranging from 1 / 2 to 1 / 128. The "1" is omitted from the table. The second and third columns include the corresponding constraints after standardization. For example, the relationship 1 / 10 gives rise to the following pair of constraints 0.141 and 1.407 in corresponding order. The fit results achieved for the various pairs of constraints are provided in the fourth to sixth columns. As it is obvious, the best model fit was indicated for $\alpha = 12$. According to this result the latent variable representing "mainly memory processes" is closely associated with the reaction time for content identity. The other reaction time seems to be due to memory processes to a very low degree only.

Table 1:
Fit results, error estimates and standardized constraints for various αs

α	Constrait for		χ^2	*df*	*RMSEA*	δ_1	δ_2
	RT-PI	*RT*-NI					
2	0.632	1.265	2501.09	2	1.530	0.05	0.34
3	0.447	1.342	287.41	2	0.517	0.05	0.17
8	0.175	1.403	3.41	2	0.003	0.05	0.09
9	0.156	1.406	1.44	2	0.000	0.05	0.09
10	0.141	1.407	0.55	2	0.000	0.05	0.09
11	0.128	1.408	0.20	2	0.000	0.05	0.08
12	0.117	1.409	0.19	2	0.000	0.05	0.08
13	0.108	1.410	0.37	2	0.000	0.05	0.08
14	0.101	1.411	0.61	2	0.000	0.05	0.08
15	0.094	1.411	0.95	2	0.000	0.05	0.08
16	0.088	1.411	1.31	2	0.000	0.05	0.08
17	0.083	1.412	1.67	2	0.000	0.05	0.08
18	0.078	1.412	2.06	2	0.007	0.05	0.08
19	0.074	1.412	2.40	2	0.019	0.05	0.08
20	0.071	1.412	2.68	2	0.025	0.05	0.08
32	0.044	1.414	5.82	2	0.060	0.05	0.07
64	0.022	1.414	9.17	2	0.082	0.05	0.07
128	0.011	1.414	11.09	2	0.092	0.05	0.07

The fit results indicated that the model fit was very good for $\alpha = 12$. All the fit statistics signify good model fit: $\chi^2(2)=0.19$, p=0.9097, $\chi^2/df=0.10$, RMSEA=.000, GFI=1.00, CFI=1.00, NNFI=1.00, SRMR=.013. Furthermore, an estimate for the variance of the second latent variables was achieved: $\phi_2 = 0.08$.

The contributions of the latent variables to the prediction of intelligence

The results of the previous section were used for additionally constraining α and ϕ_2. The variance of the second latent variable was set equal to the second variance estimate of the previous section. Furthermore, the α leading to the final variance estimate was selected for the model for investigating the relationship with intelligence. Moreover, the loading λ of the intelligence test score on the intelligence latent variable was selected in such a way that it corresponded to intelligence test reliability of .80, and the error component was adjusted accordingly. This model was found to show a good fit: $\chi^2(2)=.37$, p=0.946, RMSEA=.000, GFI=1.00, CFI=1.00, NNFI=1.01, SRMR=.012. Figure 3 provides an illustration that includes parameter estimates.

Both the exogenous latent variables (mainly perceptual processes and mainly memory processes) substantially contributed to the prediction of intelligence. The completely standardized path coefficient for mainly perceptual processes was 0.16 (t=3.13, p<.01) and for mainly memory processes 0.35 (t=6.79, p<.01). Apparently, there was a considerably stronger influence of memory processes than of perceptual processes. The multiple correlation was 0.36. These findings were to be considered as quite conservative results since in this model the error variances of the reactions times were assumed to be zero ($\delta_1 = \delta_2 = 0.00$).

Such error variances indicated that there was no shift from the manifest to the latent level, which normally characterizes latent variable analysis. In order to have such a shift to the latent level, we decided to conduct another investigation that considers reliabilities of reaction times. Depending on the number of individual measurements on which a reaction

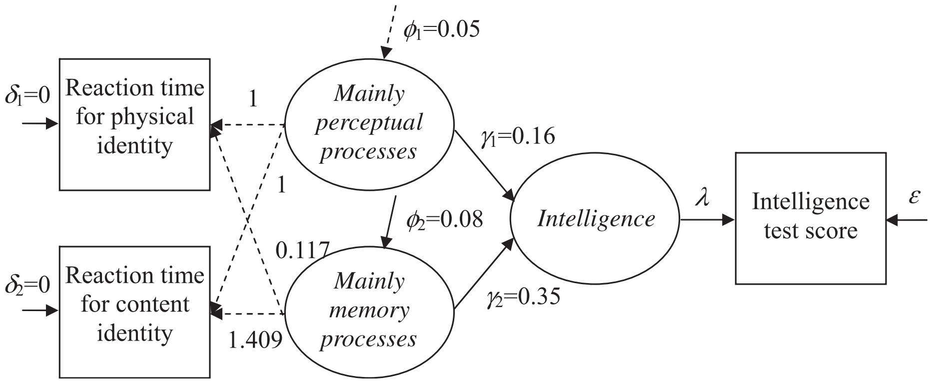

Figure 3:
Model for representing the reaction times of the Posner Task and their relationship to intelligence with completely standardized parameter estimates

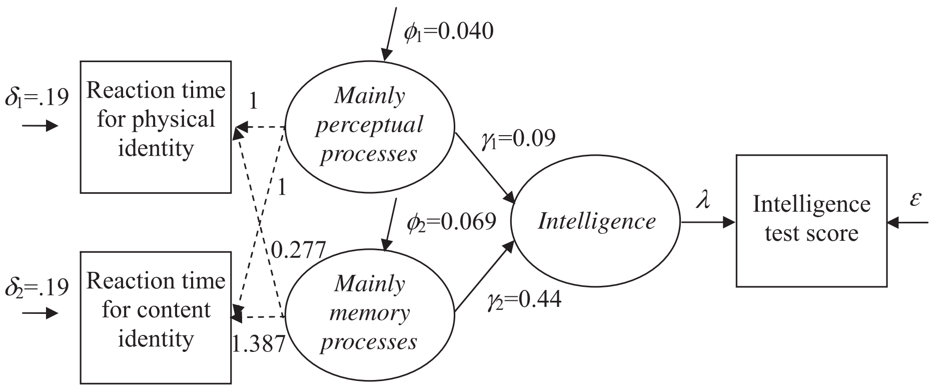

Figure 4:
Model for representing the reaction times of the Posner Task and their relationship to intelligence with completely standardized parameter estimates in assuming reaction time reliabilities of 0.90

time is based, the reliability can vary between low and high. For the further investigation we assumed reliabilities of 0.90, which was considerable, so that it could be suspected that the unknown actual reliabilities are lower. Furthermore, the error variances were selected such that completely standardized coefficients of 0.19 were obtained. This provision required the re-computation of the variances of the corresponding latent variables. The parameter estimates obtained this way are included in Figure 4.

Only one estimate of a path coefficient was substantial. The completely standardized path coefficient for mainly perceptual processes was 0.09 (t=1.39, n.s.) whereas for mainly memory processes a substantial coefficient of 0.44 (t=6.72, p<.01) was observed. The multiple correlation was 0.45. Although errors were considered, these findings may still to be perceived as conservative.

Discussion

Two processes play a major role when performing according to the two different treatments of the Posner Task. Those are perceptual and memory processes. The results of this study indicate that both processes contribute to fluid intelligence. However, according to the path coefficients, the influence of the memory processes is considerably larger than the influence of the perceptual processes. These findings are coinciding with the theories and results of Hunt, who states that both processes have an influence, or are even necessary when performing cognitive operations in completing intelligence test tasks (Hunt, 1980). However, among the two, Hunt stresses the special importance of memory processes, which is also supported by our results, and illustrated by the much larger path coefficient. Based on the results of this study, it could even be considered to neglect the influence of perceptual processes completely, since they are contributing so little to the multiple correlation.

Apart from content-related matters, the study has clearly shown the advantages of using a fixed-links structural equation model. Using the methods described above, we were able to divide the effects of the processes involved when performing according to the two different treatments of the Posner Task. By doing so, we successfully separated the memory processes from the perceptual ones, enabling us to investigate them individually. This way considerably more favourable results were achieved for the memory processes than in the original way that required the representation of memory processes by the NI-PI difference (Neubauer, 1995).

There were difficulties that had to be taken into account. One difficulty was created by having only two conditions which only produced two manifest variables. Furthermore, since the data were obtained by means of a meta-analytical procedure, the assignment of the individual measurements to two scores was not possible. Therefore the size of the error components couldn't be estimated directly. This problem was however addressed by using the step-wise procedure described above. This step-wise procedure enabled the successive estimation of relevant parameters. The parameters of the measurement model were estimated first and the parameters of the structural model subsequently. Additionally, two model versions were considered. One version assumed no error and the other one a low degree of error that is associated with high reliability. The results achieved for each model version highlighted the superior contribution of memory processes to fluid intelligence.

Because of the meta-analytical nature of our study we are not able to guarantee, that the Posner Task was carried out in exactly the same way each time, especially considering the missing information on some of the studies that were used. However, the Posner Task has been used on numerous occasions under different circumstances, and by producing very similar results, has proven to be very robust.

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