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Attention and working memory as predictors of intelligence

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Abstract

The paper reports on an investigation of attention and working memory as sources of intelligence. The investigation was concentrated on the relatedness of attention and working memory as predictors of intelligence and on the structure underlying the prediction. In a sample of 120 participants, intelligence was assessed by the Advanced Progressive Matrices [APM; Raven, J. C. (1962). *Advanced progressive matrices*. London: Lewis and Co.] and Zahlen-Verbindungs-Test [ZVT; Oswald, W. D., & Roth, E. (1978). *Der Zahlen-Verbindungs-Test (ZVT)*. Göttingen: Hogrefe]. Attention was restricted to sustained attention and measured by means of two versions of the Frankfurt Adaptive Concentration-Performance Test [FACT; Moosbrugger, H., & Heyden, M. (1997). *FAKT. Frankfurter Adaptiver Konzentrationsleistungs-Test. Testmanual. [Frankfurt Adaptive Concentration-Performance Test FACT. Test Manual]*. Bern, Göttingen: Huber]. The Exchange Test [Schweizer, K. (1996a). The speed–accuracy transition due to task complexity. *Intelligence*, 22, 115–128] and the Swaps Test [Stankov, L. (2001). Complexity, metacognition and fluid intelligence. *Intelligence*, 28, 121–143] represented working memory capacity. Structural equation modeling revealed that attention and working memory predicted overlapping parts of intelligence. The data suggested different models for APM and ZVT as criterion variable. When APM represented intelligence, the final model suggested both working memory and attention as significant predictors. In contrast, when ZVT represented intelligence, the model included only attention as significant predictor. The restriction of the models to working memory as single predictor led to an insufficient result.

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Keywords: Intelligence; Cognitive abilities; Attention; Working memory

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1. Introduction

The information-processing perspective suggests the investigation of cognitive processes as the starting point of the search for the cognitive basis of intelligence. It relates intelligence to cognitive processes, which accomplish characteristic transformations. The so-called higher mental processes are considered as being especially important for completing IQ test tasks (see Sternberg & Berg, 1986). They enable mental activities such as problem solving and reasoning, which are closely associated with intelligence (Snyderman & Rothman, 1987). Investigations focussing on these processes have revealed attention and working memory as important components of the cognitive basis. Although both attention and working memory are assumed to be unique, their characteristics suggest an overlap and give rise to the question of whether they provide independent contributions to the prediction of intelligence. Therefore, it is the aim of this paper to investigate the relationship between attention and working memory as predictors of intelligence.

Originally, attention was presented as the gate providing access to higher mental processing. Broadbent (1958) described attention as the bottleneck that needs to be passed on the way to consciousness. A more recent view suggests that attention guides the assignment of processing resources (Treisman & Gelande, 1980). Efficient assignment of processing resources means quick availability of information for higher mental processing. There are various types of resources, the availability of which for processing depends on attention (Wickens, 1984). Furthermore, the time-sharing ability enabling the simultaneous processing of several tasks is ascribed to attention (Yee, Hunt, & Pellegrino, 1991). Moreover, attentional guidance is crucial in processing according to task demands that require the coordination of several cognitive operations by providing the appropriate resources. All these functions in information processing present attention as major source of efficiency.

The relationship between measures of attention and of intelligence has been investigated repeatedly (e.g., Crawford, 1991; De Jong & Das-Small, 1995; Fogarty & Stankov, 1988; Lansman & Hunt, 1982; Lansman, Poltrock, & Hunt, 1983; Necka, 1996; Neubauer, Bauer, & Hoeller, 1992; Roberts, Beh, & Stankov, 1988; Roberts, Beh, Spilsbury, & Stankov, 1991; Rockstroh & Schweizer, 2001; Schmidt-Atzert & Ising, 1997; Schweizer & Moosbrugger, 1999; Schweizer, Zimmermann, & Koch, 2000; Stankov, Roberts, & Spilsbury, 1994). The results of these studies are not unanimous. The difference is presumably due to differences between the tests that were applied for the assessment of attention and, thus, is implicitly due to differences between the types of attention associated with these tests. Following Posner and Boise (1971), several taxonomies suggesting different types of attention have been proposed (e.g., Coull, 1998; Neumann, 1996; Sturm & Zimmermann, 2000; van Zomeren & Broubwer, 1994). Because these types of attention are considered as rather independent of each other, there is reason for expecting different kinds of relationships with intelligence. The results observed so far support the assumption of specific relationships. For example, sustained attention was repeatedly found to be correlated substantially with intelligence (e.g., Schweizer et al., 2000; Stankov et al., 1994), whereas the classical concept of divided attention did not (e.g., Fogarty & Stankov, 1988; Stankov, 1989). Furthermore, substantial correlations with intelligence were found for tests the tasks of which required quick shifts between various cognitive operations (De Jong & Das-Small, 1995; Schweizer & Koch, 2003; Stankov et al., 1994). The tasks of these tests are a bit more demanding than of typical tests of sustained attention because of their complexity. They require the continuous allocation of resources.

The working memory concept emerged because of mental activities requiring the availability of several items of information within a limited time period. Such activities relate several pieces of information to each other according to a complex plan. The authors of the classical multistore concept of memory (Atkinson & Shiffrin, 1968) argue that the short-term memory serves well as locus for such activities. However, the short-term memory as unitary store cannot account for the all the findings obtained in investigating this memory, as, for example, those provided by Baddeley and Hitch (1974). The inconsistent findings provide the basis of the working memory concept, which is assumed to be composed of three units and is widely approved (Baddeley, 1986, 1992). The first and second units are stores with different characteristics: the visual scratch pad and the phonological loop. The third unit is called central executive, which is assumed to serve attentional functions in situations requiring planning, decision making, error analysis, and adaptive behavior (Shallice & Burgress, 1993). The visual scratch pad and the phonological loop are assumed to enable the time-limited storage of information.

In elaborating the distinction between short-term and working memories, Cowan (1988, 1995) emphasized the role of attentional processes. Working memory is described as the subset of items of information, which are stored in short-term memory and are currently submitted to limited-capacity, controlled-attention processing (see also Engle, Tuholski, Lauglin, & Conway, 1999). This means that the assignment of attention to the contents of short-term memory creates working memory. Implicitly, a close connection between controlled processing of information and working memory is suggested. Consequently, working memory is essential for the mental activities that are assumed to be basic to intelligence. Working memory, with its limitations, provides the scene for errors to occur in completing intelligence test tasks (e.g., Jensen, 1982, 1992; Schweizer, 2000, 2001; Schweizer & Koch, 2001a).

There were various investigations of the relationship between measures of working memory and of intelligence (e.g., Conway, Cowan, Bunting, Therriault, & Minkoff, 2002; Engle et al., 1999; Kyllonen & Christal, 1990; Lehrl & Fischer, 1988; Necka, 1992; Schweizer, 1996a, 1996b, 2000; Schweizer & Koch, 2001a; Süß, Oberauer, Wittmann, Wilhelm, & Schulze, 2002). The available results indicate a substantial relationship between working memory and intelligence, which suggests working memory as an important part of the cognitive basis of intelligence (see also Schweizer & Koch, 2001b). However, because the most influential concept of working memory distinguishes between three units, the question arises whether the working memory as a whole or which property of which unit is especially important as source of individual differences in intelligence. Many authors emphasize the importance of working-memory capacity, which refers to working memory as a whole, because only a high capacity enables the successful completion of very complex items (e.g., Carpenter, Just, & Shell, 1990; Kyllonen & Christal, 1990). In contrast, De Jong and Das-Smaal (1995) suggest that it is the efficiency of the central executive that especially contributes to the relationship with intelligence. Furthermore, the comparison between short-term and working memories is helpful for the evaluation of the three units. In structural equation modeling, a substantial link to intelligence was only found for working memory but not for short-term memory (Engle et al., 1999). Moreover, working memory capacity was found to be a better predictor of intelligence than processing speed (Conway et al., 2002).

1.1. Are the contributions of attention and working memory unrelated or overlapping?

Because both attention and working memory showed to predict intelligence successfully, it should be investigated whether they provide unrelated contributions to the prediction of intelligence or whether their contributions overlap. Being unrelated would mean a better prediction by means of these information-processing variables than being related because unrelatedness means that separate sources of variance are predicted. However, the concepts of attention and working suggest relatedness. The attentional functions that are ascribed to the central executive of working memory (Baddeley, 1986) even signify a very close relationship instead of independence. The results of recent studies indicate that working memory capacity is related to attentional control. Consequently, it is presented as executive attention (Engle, 2002; Kane, Bleckley, Conway, & Engle, 2001). Moreover, relatedness is indicated by some of the functions ascribed to attention in information processing. Although attention has primarily been investigated and discussed in the context of perception, it is not restricted to the perceptual part of information processing. The close association of attentional selection and consciousness makes the importance of attention for higher cognitive processing especially obvious (Velmans, 1991). Moreover, the results of investigating the difference between automatic and controlled processing suggest a relationship of attention and working memory (Schneider & Shiffrin, 1977; Shiffrin & Schneider, 1977). Controlled processing is considered as being guided by attention, as being working-memory based, and as being related to intelligence. In all, the various ideas associated with the concepts of attention and working memory suggest a considerable degree of relatedness.

1.2. Are attention and working-memory tests separable?

The investigation of the relationship between the contributions of attention and working memory to the prediction of intelligence suffers from the problem of constructing tests that either exclude contributions from attention or contributions from working memory to performance. There are only tests that either pose high demands on attention and low demands on working memory or, alternatively, pose low demands on attention and high demands on working memory. To assure that the tests are appropriately classified, it is necessary to identify the demands that should characterize the tasks of attention and of working memory tests.

In considering attention, it is necessary to concentrate on sustained attention, the type of attention that is most closely related to intelligence. Sustained attention is assumed to maintain the concentration on a specific stimulus or location at a high level for quite a long time period (Coull, 1998). But the time period is shorter than the time period considered with respect to vigilance. It is the special characteristic of sustained attention that the intensity of concentration is emphasized (van Zomeren & Brouwer, 1994). A high intensity can assure that the necessary resources are available and that all the steps of a complex processing plan are executed properly. This is important whenever one processing step must follow another one according to a processing plan that is quite complex (see Carpenter et al., 1990). If attention is weakening while completing a complex task, a failure is likely to occur because processing resources are temporarily not available.

What are the characteristics of the tasks measuring sustained attention? Tests of sustained attention typically require maintaining concentration for a prolonged time period to detect specific features of the stimuli of a moderate degree of complexity. These stimuli are low demanding to processing capacity. Consequently, on the one hand, an attention test is typically low demanding that individual differences in processing capacity should not have an influence on the result. On the other hand, it is important that the attentional level is high for a prolonged period of time without interruption.

What are the characteristics of working-memory tasks? Many tasks have been constructed for investigating the properties of working memory (e.g., Baddeley, 1986; Kyllonen & Christal, 1990). With the aim of predicting intelligence in mind, emphasis should be given to characteristics of tasks, which are also important for the measurement of reasoning, problem solving, and abstract thinking (Carpenter et al., 1990; Lohman, 1998; Snyderman & Rothman, 1987). However, the tasks should not be intelligence test tasks. The most important characteristic of such tasks seems to be a high load because completing the task poses high demands on the available resources. There are various examples showing this characteristic: The Tower-of-Hanoi puzzle causes a high load (Carpenter et al., 1990). The matrix problems of Advanced Progressive Matrices (APM; Raven, 1962) cause a considerable load for information processing. Moreover, learning complex concepts means the mastering of a high load (Sweller, 1988). Consequently, working-memory tasks should cause a high cognitive load. Furthermore, the tasks should involve several units of working memory because processing by working memory characteristically includes interactions between the units that constitute it. Kyllonen (2002) additionally suggests that working-memory tasks should not stimulate learning processes; thus, only well-known materials should be used in the tasks.

One can see that two different types of demands are especially closely associated with attention and working memory, respectively. This means that there is reason for investigating whether the concepts of attention and working memory give rise to unique or overlapping contributions to the prediction of intelligence. The basis for such an investigation is provided by tasks that include the demands mentioned in the previous paragraphs. For being able to argue that attention and/or working memory contribute independently to the prediction of intelligence, one has to demonstrate that attention and/or working memory predict different portions of the variance of intelligence. Furthermore, it needs to be a demonstrated that the correlations are not due to a general predictor of intelligence, as, for example, mental speed (see Jensen, 1987, 1998). However, such a demonstration is only necessary if it is not possible to identify unique contributions due to both attention and working memory. Moreover, if the attempt to identify independent contributions to the prediction of intelligence is successful, there will be a better explanation for the individual differences in intelligence than are presently available.

1.3. Models for investigating the importance of attention and working memory

The investigation of the contributions of attention and working memory to the prediction of intelligence was already presented as the main issue of this paper. It is reasonable to construct models that represent the various ideas of the relationship between attention and working memory in predicting intelligence. The validity of the results achieved in an investigation of this issue depends on the appropriateness of the models constructed for this purpose. The models should represent the structure appropriately and enable the evaluation of the various types of relatedness among the predictors. To achieve unequivocal results, the main issue is replaced by two specific issues: the issue of relatedness among attention and working memory as predictors and the issue of the structure of attention and working memory when predicting intelligence. These issues are investigated separately.

At first, models for investigating the type of relatedness among the predictors are considered. For this purpose, attention and working memory are treated as predictors of equal status. This means that assumptions suggesting a specific structure are omitted. The first model is denoted “unrelated-predictors model” and assumes that the predictors are not correlated. The unrelated-predictors model is contrasted by a model that assumes that the predictors are correlated with each other. This second model, which is denoted “related-predictors model,” includes an additional link relating attention and working memory to each other. However, this link does not suggest a direction of influence, it just represents a correlation. The models are graphically presented in the Panels A and B of Fig. 1.

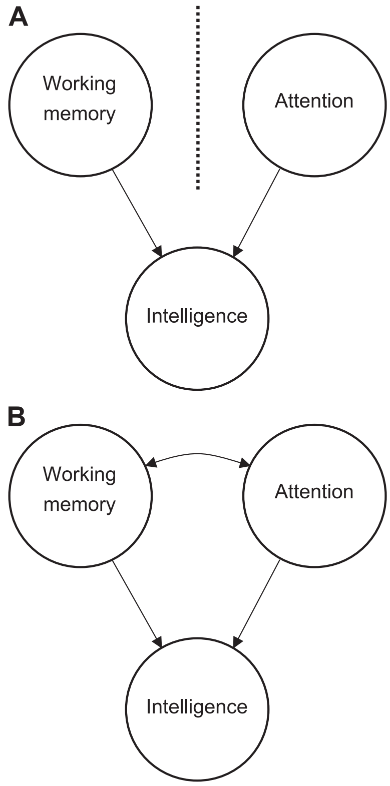

Fig. 1. (A) Unrelated-predictors model; (B) related-predictors model.

Models for investigating the issue of structure are only required if the comparison of the unrelated- and related-predictors models yields a result that is favorable for the model, suggesting relatedness of the predictors. In this case, it is necessary to investigate how attention and working memory should be arranged with respect to intelligence. The concepts presented in the previous sections suggest that working memory dominates higher mental processing in as far as higher mental processing is controlled processing whereas attention is assigned a subordinate role. It is perceived as contributing to information processing only as an integrated part of working memory. Therefore, it is reasonable to assume that attention is only linked to working memory while working memory is the only predictor of intelligence. This assumption implies that working memory mediates the influence of attention on intelligence because it excludes a direct link between attention and intelligence. This "working-memory-dominance model" will be contrasted by the "working-memory-supplemented-by-attention model," which allows attention a separate influence on intelligence. This model assumes that attention, on the one hand, contributes to working memory and, on the other hand, adds to intelligence directly. Attention favors efficient processing by providing resources that enable the continued execution of the processing plan. Furthermore, it assures that information that is obtainable from external sources is quickly made available. Because all the other assumptions of the working-memory-dominance model are considered as valid, the working-memory-supplemented-by-attention model can be regarded as an extension of the previous model. The two models are graphically represented in Panels A and B of Fig. 2.

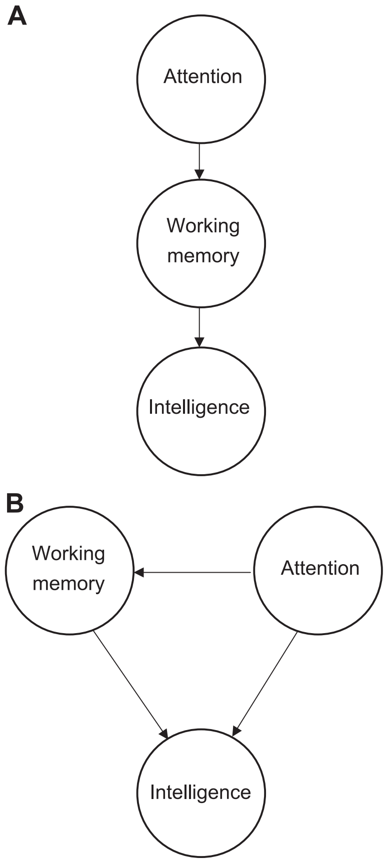

Fig. 2. (A) Working-memory-dominance model; (B) working-memory-supplemented-by-attention model.

It does not seem reasonable to consider a further model that concentrates exclusively on attention (instead of working memory) because there is general agreement that higher mental processing is regarded as being mainly limited due to working memory. The limitation that is due to attention is assumed to be restricted to the perceptual part of information processing.

2. Method

2.1. Sample

The sample included 120 participants (37 men and 83 women). The age ranged from 19 to 42 years of age, and the mean age of the sample was 28.97 years (S.D.=6.79). The mean APM score (Set II) was transformed into an IQ score by means of the tables included in the manual. This way, a mean IQ score of 116.86 (S.D.=14.99) was obtained for this sample.

2.2. Apparatus and test administration

The computerized tests were administered by means of a personal computer, which was located in a quiet room with artificial lighting at the Institute of Psychology, Goethe University Frankfurt a. M., Germany. Stimuli were presented on a 15-in. computer monitor. Three tests required the participants to respond by means of the keyboard and one test by using the mouse. Each test was preceded by an extensive instruction and practice trials to assure appropriate test knowledge. Each participant was tested individually.

2.3. Computerized tests representing working memory

2.3.1. Exchange Test

This test (Schweizer, 1996a) is a cognitive test that requires mental reorderings of simple symbols (ASCII symbols). The cognitive operations stimulated by this test are simple ordering operations that should be easily available for people of all levels of education. In the beginning of each individual trial, two lists of five symbols (e.g., List 1: +=x|− and List 2: x=|−+), arranged below each other, are presented on the computer screen. The visual angle of the stimulus is 2°. Both lists include the same symbols but differ according to the positions of these symbols. The participants are instructed to exchange the positions of neighboring symbols of one list mentally until identical sequences of symbols are achieved. Furthermore, the participants count the numbers of exchanges that are necessary for achieving identical sequences. As soon as the reordering is finished, the participants press the response key. The key pressing causes the removal of the lists from the screen. Afterwards, the participants are prompted to input the number of necessary exchanges to identify the correct responses. The participants' performance is indicated by the number of correct responses. This efficiency measure is denoted as exchange accuracy. Furthermore, the time span between stimulus presentation and response is measured and stored. It is denoted as exchange speed and can be selected for representing processing speed. However, this is only reasonable for experimental conditions showing a low degree of difficulty.

The number of exchanges depends on the difference between the two lists. The lists differ by a minimum of two symbols and a maximum of four symbols. Each number of differently arranged symbols is associated with one, two, or three different numbers of exchanges. The most easy experimental condition requires one exchange. The number of differing positions and of exchange operations of a trial is not predictable for the participants because the trials are presented in a quasi-random order. There are 12 trials per treatment level. The trials are presented separately. The participants' pressing the response key starts the trials.

There are six levels of difficulty due to the different numbers of symbols that are to be exchanged and also because of the different numbers of exchanges. These levels cause different loads in information processing. The load on information processing is mainly due to the number of intermediary results that must be maintained for later use while doing the exchanges. Because the difficulty of this test is due to the high load resulting from the maintenance and handling of many items of information, the Exchange Test is considered as test of working memory capacity.

2.3.2. Swaps Test

This test (Stankov, 2001) also requires the reordering of symbols. In this case, the symbols are capital letters. In each trial, three letters are simultaneously presented on the computer screen. The visual angle of the stimulus is 3°. The row of letters is accompanied by instructions that tell the participants that there need to be interchanges ("swaps") of the positions of the letters. This means that the original sequence of letters must be mentally replaced by a new one. There are four levels of difficulty, which differ by the number of swaps. The first level requires one swap, the second, two swaps, the third, three swaps, and the fourth, four swaps. This means that maintaining information in memory is required while executing cognitive operations.

There are four trials requiring the same number of swaps. The trials are arranged in such a way that the level of difficulty of a new trial is not predictable from the previous trial. The participants do not know the number of swaps in beforehand. The participants are instructed to perform the swaps mentally and as fast as possible. The instructions concerning the swaps are visible during the whole trial. After having arrived at the result, the participants select the array of three letters corresponding to the array achieved by the mental manipulation from a set of alternative arrays. The alternative arrays are also visible to the participants during the whole trial. The participants use the computer mouse for indicating the array that corresponds to their result. The participants' performance is measured by determining the number of correct responses. This efficiency measure is denoted swaps accuracy. Furthermore, the time between the presentation of the letters and the response is measured and stored for having a measure of processing speed. It is denoted as swaps speed. Because there is a high load resulting from the storage and manipulation of many items of information, the Swaps Test is also considered as test of working memory capacity.

2.4. Computerized tests representing attention

2.4.1. FACT

The "Frankfurt Adaptive Concentration-Performance Test" (FACT; Moosbrugger & Heyden, 1997) assesses the level of sustained attention. It requires the participant to discriminate between target and nontarget items, which are presented on the computer screen. The visual angle is 3°. The items are geometrical figures that differ with respect to shape (square or circle) and the number of dots included (two dots or three dots). The configurations "square with two dots" and "circle with three dots" serve as target items, and the configurations "square with three dots" and "circle with two dots" as nontarget items. The participants are expected to respond to the appearance of a configuration as fast as possible. In the case of a target, they should respond by pressing the "1" key of the computer keyboard and in the case of a nontarget by pressing the "0" key. Because sustained attention denotes the ability to concentrate for a prolonged time period, the time of test administration is fixed to six minutes. Two versions of FACT were used: (1) Version FACT-SR is characterized by a constant presentation mode of 10 items simultaneously. After responding to all of them, another run of 10 items appears. (2) Version FACT-E is characterized by the separate presentation of the items. Exposure time follows an adaptive presentation mode.

2.4.2. FACT-SR

In applying this version, a row of 10 configurations (=items) appears on the computer screen. An arrow indicates the configuration to which the participant has to respond, starting on the left of the row. After each response, the arrow moves to the next configuration on the right. After finishing a row, the configurations are replaced by other configurations. This test provides the reaction time as measure of efficiency, obtained by averaging the individual response times of the second to sixth minute of test administration.

2.4.3. FACT-E

In applying this version, every item (=configuration) is presented individually on the computer screen; that is, only one item is visible at a time. The presentation time of the single item depends on the participant's response. The item is removed from the screen a period of 100 ms after the response. The next item is presented 500 ms after the removal. Furthermore, presentation time of the item is adaptively adjusted to the participant's performance. A correct response leads to a decrease in presentation time, whereas an incorrect response leads to an increase in presentation time. The measure of efficiency obtainable by this test is the "liminal" presentation time of the individual items. It is achieved by averaging the time periods that a participant needed to respond correctly with P=.50 during the second to sixth minute of test administration. The two test versions vary according to the situational stress imposed on the participants; FACT-E tends to be perceived as more stressful than FACT-SR is.

2.5. Computerized tests representing intelligence

Set II of the APM of Raven (1962) and the Zahlen-Verbindungs-Test (ZVT; Oswald & Roth, 1978) were selected for representing intelligence. Many studies have revealed a high loading of APM on the general factor of intelligence (see Carroll, 1993), and therefore, APM has served in many investigations as measure of intelligence. The ZVT is a trail-making test. The authors of this test report high correlations (.40–.83) with other measures of intelligence, as for example, APM (Raven, 1962), CFT (Cattell, Weiß, & Osterland, 1997), and WAIS (Wechsler, 1955). Substantial correlations were also reported by Vernon (1993) and Vernon and Weese (1993) for English-speaking samples. Furthermore, ZVT is reported to be closely related to measures of the perceptual speed factor of intelligence.

2.6. Statistical analysis

Structural equation modeling (Jöreskog & Sörbom, 1996) was selected for investigating the prediction of intelligence by means of attention and working memory. The investigation was based on partial correlations instead on covariances. Because of the high correlation between APM and age, it was necessary to base some investigations on partial correlations (see section on Correlational analysis). Thus, the effect of age was removed from the correlations between measures representing APM, attention, and working memory.

3. Results

3.1. Descriptive statistics

The means observed for exchange accuracy, swaps accuracy, FACT-SR, and FACT-E were 43.58 (S.D.=14.23), 12.44 (S.D.=3.09), 126.85 (S.D.=30.33), and 153.61 (S.D.=46.20) in corresponding order.

To investigate whether there was an effect due to age, the participants were assigned to one of four age groups (19–23, 24–28, 29–36, or 37–42). These age groups were compared with each other by means of the F test. Furthermore, males and females were compared by means of the t test to identify gender differences. The results of these comparisons with respect to FACT-SR, FACT-E, exchange accuracy, swaps accuracy, APM, and ZVT are given in Table 1.

Table 1
F and *t* test results obtained in comparing age groups and gender groups

Measure	Age			Gender		
	F	*df*	*P*	*t*	*df*	*P*
FACT-SR	0.67	3/117	n.s.	1.28	115	n.s.
FACT-E	2.04	3/114	n.s.	2.38	116	.02
Exchange accuracy	0.70	3/113	n.s.	1.77	115	n.s.
Swaps accuracy	0.25	3/116	n.s.	0.55	118	n.s.
APM	14.59	3/115	.001	0.97	118	n.s.
ZVT	1.33	3/116	n.s.	1.77	115	n.s.

The *F* test results showed no difference according to FACT-SR, FACT-E, exchange accuracy, swaps accuracy, and ZVT, whereas APM was found to differ with respect to the four age groups. This *F* test result even suggested a considerable difference. The *t* test results indicated no gender difference according to FACT-SR, exchange accuracy, swaps accuracy, APM, and ZVT, whereas males and females showed to differ slightly according to FACT-E.

Obviously, there was a small effect of gender on FACT-E results and a larger effect of age on APM results.

3.2. Correlational analysis

Pearson correlations between APM, ZVT, exchange accuracy, swaps accuracy, FACT-SR, and FACT-E were computed. These correlations are presented in Table 2.

All the correlations reached the level of significance ($P<.05$) and were positive. The highest correlation was observed between the two FACT measures. This correlation reached a size that could be expected for parallel measures of a trait. The correlation between the two measures of intelligence, APM and ZVT, was lower than expected. Although this correlation indicates a positive relationship between APM and ZVT, its size suggested that the tests represented two different facets of intelligence. This suggestion was confirmed by the observation that this correlation was even surmounted by the correlations between APM and ZVT, on the one hand, and FACT measures on the other hand. Furthermore, it is to be noted that exchange and swaps accuracies showed a positive correlation.

Table 2
Pearson correlations between APM, ZVT, exchange accuracy, swaps accuracy, FACT-SR FACT-E and age, and *g* loadings (N=120)

	APM	ZVT	E	S	FSR	FE	*g*
APM	1.00						.61
ZVT	.41	1.00					.65
Exchange accuracy (E)	.38	.33	1.00				.52
Swaps accuracy (S)	.28	.24	.43	1.00			.37
FACT-SR (FSR)	.44	.52	.37	.21	1.00		.81
FACT-E (FE)	.51	.56	.37	.21	.82	1.00	.87
Age	−.52	−.12*	−.02*	.03*	−.08*	−.23	

* These correlations do not reach the 5% level of significance.

To prevent the effect of age from contributing to the results of structural equation modeling, correlations controlled for age were used in the further calculations with respect to APM. This led to a small reduction of the correlations between the FACT scores and the measures of intelligence. As a result of this provision, a correlation of .44 was obtained for the combination of APM and FACT-E, a correlation of .49 for the combination of APM and FACT-SR, a correlation of .48 for the combination of ZVT and FACT-E, and a correlation of .46 for the combination of ZVT and FACT-SR.

3.3. Structural equation modeling: the issue of relatedness

The structural models that were investigated corresponded to the first to fourth models, which were presented in the Introduction. Because attention, intelligence, and working memory were latent variables and represented by two measures each, it was necessary to select an appropriate measurement model. The congeneric model of measurement (see Alwin & Jackson, 1980), which included no restrictions, was not useful because this model required the estimation of too many parameters. The alternatives were the tau-equivalent model of measurement and the parallel model of measurement (see Alwin & Jackson, 1980). The less restrictive one of the two models was suggested for this study.[1] It was the tau-equivalent model of measurement that was given preference. This model required that the loadings of each pair of variables showed the same size while the corresponding error components were allowed to differ in size.

In investigating the issue of relatedness, Models 1 and 2 (unrelated-predictors and related-predictors models, respectively) were applied to the data. For none of these models was a sufficient degree of fit observed. The first model led to a χ^2 of 21.71 (*df*=10), an RMSEA of .10, a GFI of .94, and an AGFI of .88, and the second model to a χ^2 of 6.94 (*df*=9), an RMSEA of .00, a GFI of .98n and an AGFI of .96. Apparently, the first model did not represent the data sufficiently well, whereas the second model did. Although the related-predictors model showed a good degree of fit, this model proved to be inappropriate because of the low gamma coefficients. The gamma coefficients indicated the sizes of the links between the independent and the dependent latent variables. These coefficients did not reach the level of significance [attention–intelligence: .60 (*t*=1.01, n.s.); working memory–intelligence: .51 (*t*=.89, n.s.)]. The main reason for the lack of significance was the large sizes of standard errors, which were due to the low correlation between APM and ZVT. An increase of this (partial) correlation from .42 to .49 would have solved the problem.

As a consequence of this observation, each model presented in the Introduction was replaced by two specific model versions, including only one indicator of intelligence. Because neither APM nor ZVT was perfectly reliable, the error components were adjusted in considering the reliability of these measurement instruments. These components were fixed in such a way that they were equal to the difference between one and the square of the corresponding reliability coefficients. The manuals of APM and ZVT suggested a minimum reliability of .83 for APM and of .95 for ZVT. Accordingly, the error component of APM was set to .31 and the error component of ZVT to .10. All the other details corresponded to the details of the unspecific model. The results that were obtained for the two versions of Models 1 and 2 are provided in Table 3.

The results obtained for the two specific versions of the unrelated-predictors model did not suggest a sufficient degree of fit. All the statistics were beyond the acceptable range. In contrast, a good model fit

[1] The authors are grateful to an anonymous reviewer who convinced us that the tau-equivalent model is appropriate.

Table 3
Goodness-of-fit results obtained for the versions of the unrelated-predictors (Model 1) and the related-predictors (Model 2) models

Version	χ^2	df	RMSEA	GFI	AGFI
Independent-predictors model					
APM	19.98	6	.140	.94	.84
ZVT	19.30	6	.137	.94	.85
Dependent-predictors model					
APM	4.16	5	.000	.99	.96
ZVT	4.22	5	.000	.99	.96

was indicated for the two specific versions of the related-predictors model; all the statistics were within the acceptable range. To provide information concerning the issue of relatedness, chi-square-difference tests were computed. A value of 15.82 (df=1) was found for the APM version and a value of 15.08 (df=1) for the ZVT version. In both cases, the difference was highly significant. Apparently, the related-predictors model fitted better to the data than the unrelated-predictors model did.

A correlation of .50 between attention and working memory was found for the related-predictors model. Furthermore, it was interesting to observe path coefficients of .36 (t=2.73, P<.01) and .54 (t=3.52, P<.01) relating attention and working memory, respectively, to intelligence in the APM version of the related-predictors model. In the ZVT version of the related-predictors model, the path coefficient for attention of .50 (t=4.46, P<.01) was significant, but in contrast, the path coefficient of .22 (t=1.72, n.s.) relating working memory to intelligence was insignificant. Apparently, attention contributed to the prediction of intelligence in both versions, whereas working memory contributed in the APM version only.

3.4. Structural equation modeling: the issue of structure

The models for investigating the issue of structure were constructed in the same way as the models for investigating the issue of relatedness. Analogously, attention and working memory were represented by two measures, each according to the tau-equivalent model of measurement. Furthermore, in representing

Table 4
Goodness-of-fit results obtained for the versions of the working-memory-dominance (Model 3) and the working-memory-supplemented-by-attention (Model 4) models

Version	χ^2	*df*	RMSEA	GFI	AGFI
Working-memory-dominance model					
APM	8.84	6	.060	.97	.93
ZVT	13.83	6	.115	.96	.89
Working-memory-supplemented-by-attention model					
APM	4.16	5	.000	.99	.96
ZVT	4.22	5	.000	.99	.96

APM and ZVT, the error components were fixed, as described in the previous section. Moreover, structural equation modeling was based on the partial correlations corrected for age.

In investigating the issue of structure Models 3 and 4 (working-memory-dominance and working-memory-supplemented-by-attention models, respectively) were applied to the data. Again, the APM and ZVT versions were constructed and investigated instead of the unspecific model. The results observed for these versions are provided in Table 4.

The results obtained for both versions of the working-memory-dominance model did not suggest a sufficient degree of fit. All the statistics were beyond the acceptable range. In contrast, a good degree of fit was indicated for both versions of the working-memory-supplemented-by-attention model, in which almost all the fit statistics indicated a good fit. The differences between the statistics of the two types of models were considerable. Because the two types of models only differed by one link, it was possible to

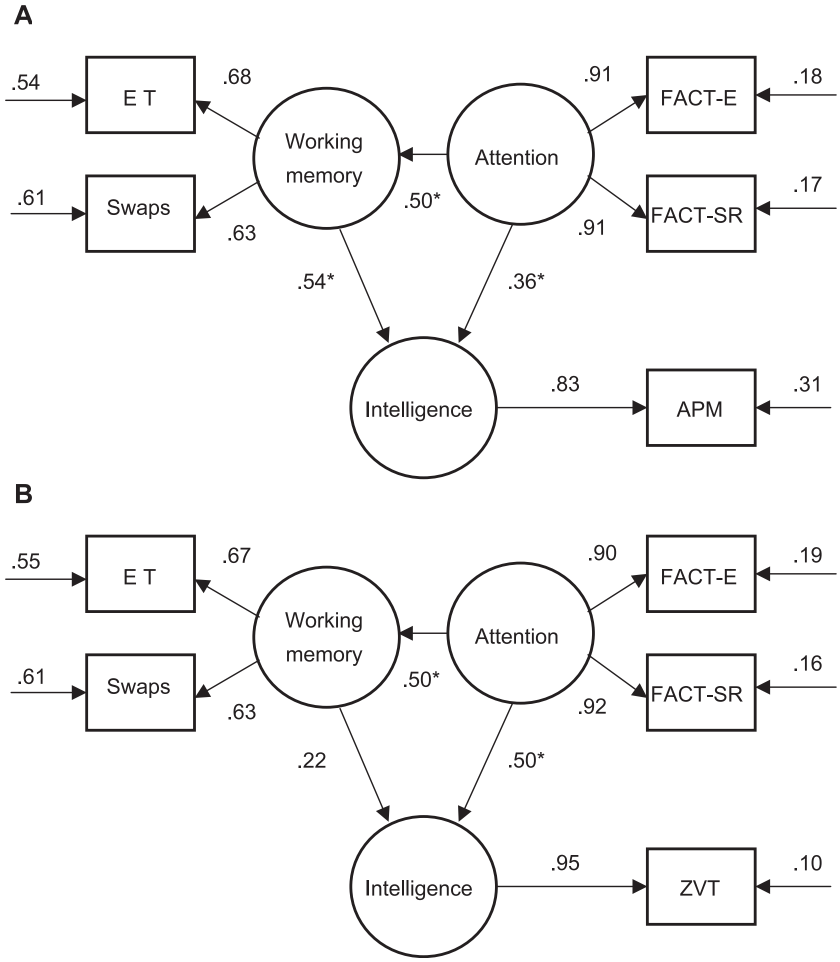

Fig. 3. (A) APM version of Working-memory-supplemented-by-attention Model with parameter estimates (standardized solution); (B) ZVT version of working-memory-supplemented-by-attention model with parameter estimates (standardized solution).

compare them by computing χ^2 differences. A χ^2 difference of 4.68 (*df*=1) was found for the APM version, and a χ^2 difference of 9.61 (*df*=1) for the ZVT version. In both cases, the result was significant. Apparently, the working-memory-supplemented-by-attention model fitted better to the data than the working-memory-dominance model did.

The versions of the working-memory-supplemented-by-attention model, including the parameter estimates, are graphically represented in Fig. 3.

All the parameters in the structural model of the APM version reached the level of significance. Apparently, both the contributions of attention and working memory to intelligence were considerable. Attention and working memory predicted 61% of the variance of intelligence on the latent level. The meaning of this result was that the total variance explained jointly by both predictors for the predicted variable (intelligence) was 0.61, and the residual variance 0.39. The coefficients of the links (=direct effects) suggested working memory as the more important predictor (.54) and attention as the less important predictor (.36). In contrast, the parameters of the ZVT version suggested that only attention contributed to the prediction of intelligence [coefficient of attention: .50 (t=4.46, P<.01); coefficient of working memory: .22 (t=1.73, n.s.)]. The ZVT version of the working-memory-supplemented-by-attention model predicted 41% of the variance of intelligence if both predictors were included. The meaning of this result was that the total variance explained jointly by both predictors for the predicted variable (intelligence) was 0.41 and the residual variance 0.59. The elimination of the contribution of working memory reduced the prediction to 38% of the variance of intelligence. Only in the case that attention was removed as predictor, working memory contributed to the prediction of intelligence represented by ZVT.

4. Discussion

The investigation of the relationship between working memory and attention in predicting intelligence revealed the expected relatedness of the predictors that showed to be neither uncorrelated nor appropriate for replacing each other. This result is remarkable, insofar as during the last decade, research was increasingly concentrated on working memory (see Kyllonen, 1996), while the other components of information processing were presented as subordinate. Emphasizing the importance of working memory means giving preference to the ability of solving complex problems by performing cognitive operations while maintaining information that is essential for further processing. Furthermore, it means giving special weight to the ability of coordinating and supervising cognitive operations during processing that occur as part of the functioning of working memory (e.g., De Jong & Das-Small, 1995; Yee et al., 1991).

The ability of performing consistently on a high level for a prolonged period of time is probably the most important one among the neglected components of information processing. The disregard of this ability is not really justified because there is work that emphasizes its contribution to information processing. For example, the study by Carpenter et al. (1990) revealed that solving complex problems, like the Tower-of-Hanoi puzzle, requires the design of a complex plan, which includes many cognitive operations and the careful execution of this plan. Carpenter et al. suggest the "goal-recursive strategy" for solving this puzzle. The person completing this puzzle is forced to execute this plan without a break because the temporary removal of attentional and storage resources from processing would mean a breakdown. Consequently, the ability of maintaining attention at a high level is especially important when a complex task needs to be completed. This ability may be less important for other tasks applied in the assessment of intelligence (see Carroll, 1993), as, for example, memory tasks or psychomotor tasks. In all, being able to maintain attention for a long time at a high level is important whenever complex mental activities are to be performed. This applies to mental activities such as problem solving and reasoning, which are closely associated with intelligence (Snyderman & Rothman, 1987).

The results of this study partly support the assumptions of the models of working memory. A substantial link between attention and working memory was observed. It indicates that measures of working memory include a component that is also represented by measures of attention. This is the evidence supporting the original position of Baddeley (1986, 1992). Furthermore, there is the observation that the contribution of working memory to intelligence is changing from APM to ZVT. This observation is in agreement with the interpretation of working memory of Cowan (1988, 1995). While correlational analysis suggested that working memory contributed to the processing of ZVT tasks in the same degree as to the processing of APM tasks, ZVT tasks proved to be less demanding on working memory than APM tasks were. In the case of ZVT tasks, attention seems to provide the main processing resources. These results make obvious that the contribution of attention and especially of working memory depends on the task demands. Furthermore, it is to be added that performance in completing ZVT tasks may be influenced by mental speed (Neubauer, 1997).

Sustained attention was selected out of a variety of alternative types of attention for this study. The results assure the appropriateness of the decision for sustained attention. Substantial correlations with the measures of intelligence were found. This means that sustained attention is important for completing the tasks of both tests, APM, and ZVT. In both cases, it is necessary to perform at a high level for a prolonged period of time. The period of time which is normally required for completing ZVT tasks is usually longer than that necessary for completing APM tasks. The difference provides an explanation for the observation of larger correlations of the measure of attention with ZVT than with APM. The other types of attention that are included in the schemes provided by Coull (1998), for example, divided attention, selective attention, and vigilance, are also important for information processing in general. However, the available evidence suggests that these types possess a lower degree of importance for the completion of complex tasks, such as APM and ZVT tasks. Success with respect to the demands of these tasks is to a considerable degree due to sustained attention.

In this study, age proved to be a crucial variable: The effect of age was to be controlled statistically. Although the age range was limited, age turned out to be highly correlated with intelligence. Age has been shown to be related to biologically based measures of performance. For example, processing time was found to increase with age (Salthouse, 1996). An effect of age on the result of APM can be expected if participants complete APM tasks especially fast, because in this case, younger participants should attain better results than older participants do. Although the standard presentation time was selected for the administration of APM, a considerable number of participants may have tried to complete the test rather fast so that differences in processing speed may have influenced the results. This is a hypothesis that is reasonable but can no more be verified. Furthermore, there are new findings suggesting a general age-related decline in cognitive functioning (Salthouse, 2001). Such a decline can cause substantial correlations between measures of general cognitive abilities and measures of cognitive performance. Taking into account these extra sources of correlation, it was especially interesting to find reasonable results after controlling age.

Overall, it is to be noted that about half of the variance of individual differences in intelligence can be explained on the latent level by means of attention and working memory in this study. Although this is a considerable proportion of the variance of individual differences, there is still a large proportion that needs to be predicted. To achieve a higher rate in prediction, other sources have to be considered. In a recently published article, Detterman (2002) has presented a list of further explanations of the general factor of intelligence, which surely applies to individual differences in intelligence as well. This list suggests multiple sources besides single sources and additional properties of the system as a whole. So there are starting points for future research that presumably further improves the prediction of intelligence.

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