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ORIGINAL ARTICLE

Extending the model of cognitive estimation with spatial abilities

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Abstract

In everyday life we have to rely on cognitive estimation as exact knowledge is often lacking. The aim of our study was to examine if spatial abilities like mental rotation and visuoconstruction have substantial associations with cognitive estimation so that current models of cognitive estimation might have to be extended.
We examined a healthy representative German sample (n=50) with measures of cognitive estimation, mental rotation, visuoconstruction, and long-term memory.
A confirmatory factor analytic model on variable level and cluster analysis on individual level revealed associations between spatial abilities and cognitive estimation which were not described previously in clinically oriented studies. Demographic characteristics like age, gender, and education should also be further examined in cognitive estimation.
Contemporary models of working memory are not able to explain spatial manipulations that are necessary for cognitive estimation.

INTRODUCTION

In everyday life we often do not have exact knowledge in several areas. We have to estimate the time it takes to reach a certain destination, distances while driving a car, or the amount of food we have to buy. Consequently, cognitive estimation is an important but underestimated cognitive ability.

Models of cognitive estimation suppose that different neuropsychological domains are involved in this process. Brand *et al* (2002) think that an estimation task is stored in working memory and that all relevant information regarding the task is retrieved from declarative long term memory (Figure 1). The retrieved information can be numeric and/or semantic and must then be connected. If the information does not suffice then further information has to be retrieved. The process of retrieval is dependent on different strategies. One possible strategy might be to compare the estimation task to a stored prototypical object or process. The generated answer is then monitored by a plausibility check which is postulated to take place in a control loop between working memory and a central processing control. The main function of this central processing control is to detect mistakes and to possibly initiate a further search for more precise answers in declarative long term memory. When no implausibilities were detected, the answer is transferred in to an output code.

The model of Brand *et al* (2002) has parallels to common memory models (Baddeley 2009; Baddeley & Hitch 1974; Squire 1987). They all have a central processing unit which is interconnected with working memory, although working memory in the model of Brand *et al* (2002) is of a more global nature and not further elaborated. The central processing control can be regarded as a synonym for executive functions. Executive functions are a heterogenous construct with no stringent definitions. They are supposed to monitor behavior and influence decision making and problem solving (Baddeley & Della Salla 2003; Monsell & Driver 2000). In this context, Baddeley and Wilson (1988) have introduced the term „dysexecutive syndrome". This syndrome contains cognitive, behavioral, and emotional impairments after uni- or bilateral frontal brain damage. These can be widespread and affect memory, attention, selective processing of information, social behavior, and problem solving.

In a study applying functional magnetic resonance tomography (fMRT) Horacek *et al* (2010) used the Cognitive Estimation Test (CET) and other cognitive estimation tasks to explore which brain regions are involved in this process. They found activation in the same brain regions that are involved in mental rotation. This is the first study that reported such associations. So far, spatial abilities are not represented in models of cognitive estimation. In contrast to the visuospatial components of models of working memory, spatial abilities are more specialised distinct cognitive abilities (Groh-Bordin & Kerkhoff 2009). They need working memory capacity but they go far beyond storage and basic mental manipulations of visual and spatial information.

In our study we focus on the association between mental rotation and visuoconstructive abilities with cognitive estimation because of their theoretical and practical importance regarding spatial abilities. Mental rotation is the ability to perform two or three dimensional manipulations of objects. It was shown that the duration of mental rotation was largely equivalent to real roation (Shepard & Metzler 1971). Several studies point to a connection between mental rotation and motor processes (Cohen *et al* 1996; Wexler *et al* 1998). Furthermore, the severity of motor impairment in Parkinson´s disease was associated with mental rotation (Hirsch *et al* 2003).

Visuoconstructive abilities are needed when spatial relations are reproduced manually like copying objects. They depend on different perceptive and cognitive functions like vision, visuospatial perception, motor processes, and higher cognitive functions (Goldenberg 2007). When visuoconstructive abilities are impaired, there is a high probability that other spatial abilities are also affected (Kerkhoff & Marquardt 1995).

The aim of our study was to examine if spatial abilities like mental rotation and visuoconstruction have substantial associations with cognitive estimation so that current models of cognitive estimation might have to be extended.

MATERIALS AND METHODS

Subjects

We intended to include a representative sample of healthy German adult subjects older than 18 years with no visual impairment, no serious chronic diseases, and who did not take psychoactive medication. Our sample (n=50) consisted of 25 females and 25 males. The average age of the sample was 44.7 years (sd 16.0) with a minimum of 18 and a maximum of 75 years. Thirteen (26%) had a low graduation, 24 (48%) a medium, and 13 (26%) had a high graduation. Compared to the German population this sample can be regarded as representative (Gehrke *et al* 2007).

Our study corresponds to the Declaration of Helsinki of 1975, as revised in 1983. The study was approved by the local ethics committee at the Department of Psy-

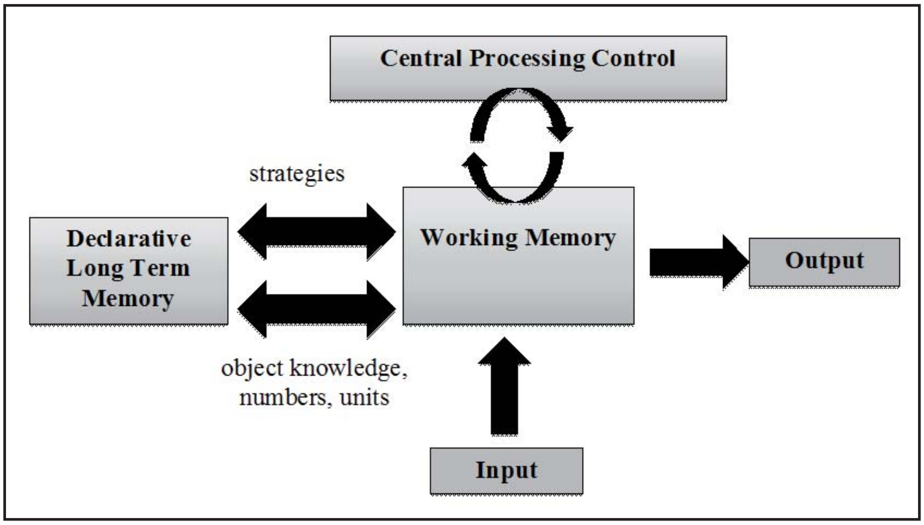

Figure 1. Model of cognitive estimation (after Brand, Kalbe & Kessler (Brand *et al* 2002)).

chology, Philipps University Marburg, Germany. All participants gave their written informed consent. Subjects received no gratification for their participation.

Test of Cognitive Estimation (TKS)

The Test of Cognitive Estimation (TKS) by Brand *et al* (2002) consists of 16 items covering areas height, number, weight, and time with four pictures and/or questions each. It was standardised with data from a sample of 171 healthy individuals with a mean age of 56.1 years. A point is scored if an estimation lies within a predefined range. The maximum score is 16 points. The minimum score for an average performance is 11 points. The internal consistency is 0.77 (Cronbach-α), item-total correlations range from r_{it}=0.13 to r_{it}=0.52, correlations to the subtest "Information" of the Wechsler Adult Intelligence Scale range from 0.28 to 0.46 in healthy subjects and clinical groups.

Mental Rotations Test (MRT-A)

The Mental Rotations Test (MRT) (Peters *et al* 1995; Vandenberg & Kuse 1978) measures the ability to mentally rotate abstract objects. The participants have to decide which two out of four three dimensional cube figures are rotated versions of a standard figure. One point per task is scored only if these two rotated versions are correctly identified. The maximum score is 24 points. The time constraint was 6 minutes for 12 tasks with a short break between two parts of 12 tasks each.

The internal consistency is 0.88 (Kuder-Richardson-20), the retest reliability after one year is between r=0.70 to r=0.83 and there are substantial correlations to other spatial tests (Vandenberg & Kuse 1978).

Block design (Wechsler Adult Intelligence Scale, WAIS)

Visuoconstructive skills were assessed with the subtest „block design" of the German version of the Wechsler Adult Intelligence Scale (WAIS-III) (von Aster *et al* 2006). The individual raw score can be transformed to a standardized score with a mean of 10 and a standard deviation of 3. The internal consistency is 0.78 (Cronbach-α), the split-half reliability is r_{tt}=0.89. Item intercorrelations are in the middle range. Correlations to other visuoconstructive measures range between r=0.75 and r=0.83 (Bodenburg 1994).

Information (Wechsler Adult Intelligence Scale, WAIS)

The subtest "Information" of the German version of the Wechsler Adult Intelligence Scale was used to assess acquired knowledge stored in long term memory which is represented in current models of cognitive estimation. It consists of 28 questions regarding events, objects, and people. The individual raw score can be transformed to a standardized score with a mean of 10 and a standard deviation of 3. Split-half reliability is r_{tt}=0.91. The highest correlation with other WAIS subtests is r=0.71 with subtest "Vocabulary", the lowest correlation is r=0.28 with "Picture Completion".

Statistical methods

We used structural equation modelling to test our hypothesised extended model of cognitive estimation on variable level. A confirmatory factor analysis with the method of Unweighted Least Squares (ULS) was selected as the standardised scores of the WAIS subtest "Block design" were not normally distributed and the ULS method makes no distributional assumptions (Blunch 2008). Several model fit indices were calculated. The root mean square residual (RMR) measures the mean absolute value of the covariance residuals. Values less than 0.05 indicate a good model fit. The standardised RMR (SRMR) removes scaling effects in the RMR. Values less than 0.10 indicate a good model fit (Weiber & Mühlhaus 2009). The Global Fit Index (GFI) can be considered as a measure of the proportion of variance and covariance that a given model is able to explain. The adjusted global fit index (AGFI) takes the number of parameters used in computing the GFI into account. In both indices, values >0.90 signal a good model fit. Spearman correlations were used to examine associations between the neuropsychological measures.

On individual level we performed k-means cluster analyses generalised to all scales of measurement with squared euclidean distances (Bacher *et al* 2010). The k-means procedure identifies relatively homogenous subgroups while maximizing the variability between clusters. The appropriateness of a cluster solution can be evaluated by several statistical measures (F value, eta^2) (Schendera 2009).

We used SPSS 19.0, AMOS 19.0 and ALMO 14 (www.almo-statistik.de) for our analyses.

Results

Descriptives

Table 1 shows descriptive data of the four neuropsychological measures. All means were in the normal range. The standard deviation of the MRT-A was quite high indicating higher variability within the sample. We also found higher MRT-A scores in men compared to women (Hirsch *et al* 2003).

Confirmatory Factor Analysis

We performed a confirmatory factor analysis with „cognitive estimation" as a latent variable and TKS and

Table 1. Means, standard deviations, and range of TKS and MRT-A raw scores and of Block design and Information standardised scores.

	mean	sd	range
TKS	12.14	1.99	6–16
MRT-A	12.60	6.20	3–24
Block design	10.66	2.92	3–16
Information	9.22	2.80	4–15

MRT-A raw scores and WAIS subtests “Block design” and “Information” standardised scores as dependent variables (Figure 2). Fit indices SRMR and RMR were 0.058 each, the GFI was 0.986, and the AGFI was 0.932 which all indicate an acceptable model fit. Standardised factor loadings were 0.38 for WAIS subtest “Information”, 0.41 for the TKS, 0.67 for the MRT-A, and 0.69 for WAIS subtest “Block design”.

The highest intercorrelation (Spearman) occurred between MRT-A and Block design (r=0.39, *p*=0.006), followed by the correlation between TKS and MRT-A (r=0.35, *p*=0.01). Correlations between TKS and subtests Block design and Information on the other side were 0.12 (*p*=0.40) and 0.11 (*p*=0.45), respectively. The latter obviously capture different aspects of the latent construct.

Cluster analysis

The variables used for classification on individual level were the same as in our confirmatory factor analysis. A three cluster solution which was best interpretable resulted in an F value of 17.57 and an eta^2 of 0.428, meaning that 42.8% of the variance can be explained by this partitioning. Consequently this cluster solution possesses good quality criteria (Jaccard & Becker 2009).

Cluster 1 consists of individuals with average performance in the Test of Cognitive Estimation, average mean mental rotation scores, average mean Block design standardised scores, and average mean Information standardised scores. The characteristics of this group regarding age, gender, and education correspond closely to the German population.

Table 2. Characterisation of the three clusters by means and standard deviations of classification variables.

	Cluster 1	Cluster 2	Cluster 3
n	21 (42%)	13 (26%)	16 (32%)
TKS	12.57 (1.26)	13.23 (1.72)	10.69 (2.08)
MRT	12.81 (5.40)	18.31 (4.29)	7.69 (3.75)
Block design	11.81 (1.53)	12.23 (2.22)	7.88 (2.74)
Information	11.67 (1.64)	7.23 (1.76)	7.63 (2.09)

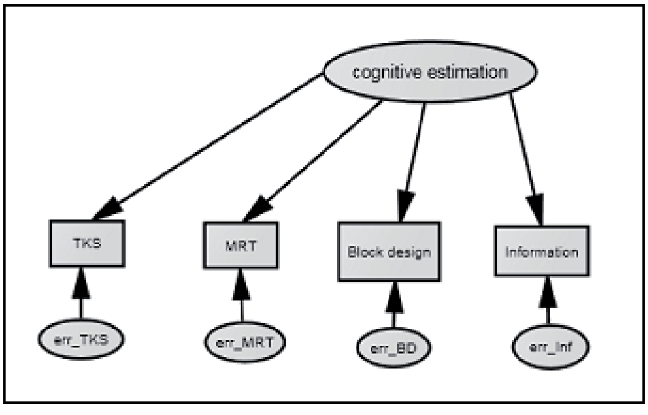

Figure 2. Confirmatory factor analytic model of cognitive estimation.

Cluster 2 had the highest TKS mean score, above average mean MRT scores, average mean Block design standardized scores, and below average mean Information standardized scores. These were mainly younger men with a medium educational level.

Cluster 3 had the lowest TKS mean score, below average mean MRT scores, the lowest mean Block design standardized scores, and the lowest average mean Information standardized scores. In this group there were mainly women with lower education.

These results on individual level also show the interrelatedness of spatial abilities with cognitive estimation but also the influence of demographic characteristics like age, gender, and education.

Discussion

We were able to support our assumption of an extended model of cognitive estimation which contains additional spatial abilities like mental rotation and visuoconstruction. This was shown on variable level by confirmatory factor analysis and on individual level by cluster analysis. The latter results propose that further variables like age, gender, and education might have associations to cognitive estimation. Hardly any studies were conducted in these areas so far (Crawford *et al* 2000; O‘Carroll *et al* 1994).

A limitation in our analyses might have been the sample size. For confirmatory factor analysis larger sample sizes are proposed, although these recommendations often are based on rules of thumb (Weiber & Mühlhaus 2009) and other studies with comparable sample sizes also produced theoretically plausible and obviously stable results (Richardson *et al* 2011). No clear recommendations regarding sample size exist in cluster analysis (Schendera 2009).

By the example of mental rotation which has the highest correlation to the Test of Cognitive Estimation and is a specialised spatial ability, we try to illustrate our opinion that current models of working memory are not able to represent cognitive manipulations that are also necessary for cognitive estimation. A meta-analysis supports the assumption that mental rotation depends on analog spatial representations and motor simulation as brain regions known to be involved in these tasks were also activated in mental rotation tasks (Zacks 2008). For example, the visuospatial sketchpad (VSSP) in the multi-component model of working memory by Baddeley & Hitch (1974) is said to maintain and manipulate visual and spatial information (Repovs & Baddeley 2006). It is therefore a system with passive and active components that provides the basis for complex cognitive abilities which are far more specialised than such basic mechanisms (Bruyer & Scailquin 1998).

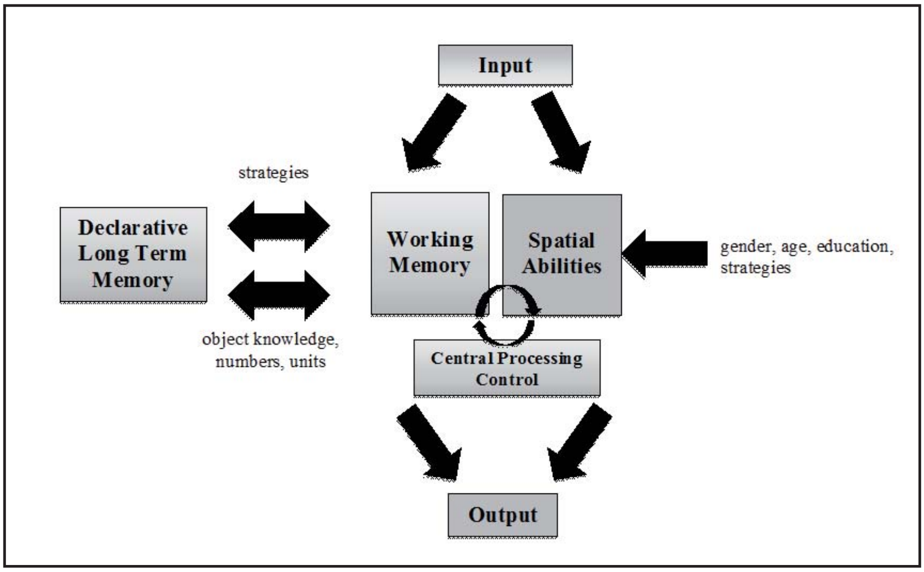

Figure 3. Extended model of cognitive estimation.

Support for this assumption also stems from an electrophysiological study by Prime and Jolicoeur (2010). They found that mental rotation was based on utilising representations stored in visual short-term memory. Spatial manipulations obviously took place in other spatial neural networks than those involved in spatial working memory. A neurocognitive network model with parallel processing was best able to fit fMRI data in the study of Ecker *et al* (2008). Whether information processing during mental rotation is mainly visual or spatial is still a matter of debate (Liesefeld & Zimmer 2012). This demonstrates that current models of working memory do not capture complex spatial abilities like mental rotation. Consequently, the model of cognitive estimation should be augmented with these cognitive skills.

Therefore, we propose to extend the current model of cognitive estimation with spatial abilities (Figure 3). We assume that the estimation task as an input also activates spatial abilities which depend on memory processes but are a distinct cognitive activity. The central processing control unit provides the allocation of attentional resources and evaluates the estimation that resulted from the interaction between spatial abilities, working memory, and information retrieved from declarative long term memory.

The estimation output therefore does not solely depend on memory processes but also on spatial abilities which seem to be associated with demographic characteristics and the differential use of strategies.

This model is supported by the – to our knowledge – only fMRT study of Horacek *et al* (2010) on cognitive estimation which found an involvement of brain regions in this task that are also activated during mental rotation. Further imaging research in cognitive estimation has to be done that might also consider the influence of demographic characteristics and age in detail.

Conflict of interest statement

The authors declare that they have no conflicts of interest.

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