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A key role for experimental task performance: Effects of math talent, gender and performance on the neural correlates of mental rotation

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ABSTRACT

The neurophysiological mechanisms underlying superior cognitive performance are a research area of high interest. The majority of studies on the brain–performance relationship assessed the effects of capability-related group factors (e.g. talent, gender) on task-related brain activations while only few studies examined the effect of the inherent experimental task performance factor. In this functional MRI study, we combined both approaches and simultaneously assessed the effects of three relatively independent factors on the neurofunctional correlates of mental rotation in same-aged adolescents: math talent (gifted/controls: 17/17), gender (male/female: 16/18) and experimental task performance (median split on accuracy; high/low: 17/17). Better experimental task performance of mathematically gifted vs. control subjects and male vs. female subjects validated the selected paradigm. Activation of the inferior parietal lobule (IPL) was identified as a common effect of mathematical giftedness, gender and experimental task performance. However, multiple linear regression analyses (stepwise) indicated experimental task performance as the only predictor of parietal activations. In conclusion, increased activation of the IPL represents a positive neural correlate of mental rotation performance, irrespective of but consistent with the obtained neurocognitive and behavioral effects of math talent and gender. As experimental performance may strongly affect task-related activations this factor needs to be considered in capability-related group comparison studies on the brain–performance relationship.

1. Introduction

Interindividual variance of performance in a given task (e.g. accuracy, speed) is a ubiquitous psychological phenomenon. Any functional or structural brain property which co-varies with task performance can be addressed as a *neural correlate of performance* (NCP) of the respective task. Searching NCPs is currently a highly active field in neurocognitive research (Deary, Penke, & Johnson, 2010; Haier, 2009; Neubauer & Fink, 2009; Rypma & Prabhakaran, 2009).

Neuroimaging research on NCPs has largely focused on the effects of capability-related group factors (e.g. intelligence, talent, or expertise) on task-related brain activations (Grabner, Neubauer, & Stern, 2006; Lee et al., 2006; Singh & O'Boyle, 2004). Capability effects have been reported since the very beginning of functional neuroimaging (Charlot, Tzourio, Zilbovicius, Mazoyer, & Denis, 1992). Since stimulation tasks which address the specific knowledge or skills of high-capability subjects are beyond reach for standard subjects, the applied tasks usually refer to elementary cognitive abilities that presumably contribute to the respective capability of interest. However, it is debatable whether a capability-related group effect on experimental task performance (i.e. behavioral performance during scanning) validates the supposed capability-task relationship or rather confounds the group factor (Bell, Willson, Wilman, Dave, & Silverstone, 2006; Butler et al., 2006; Jordan, Wustenberg, Heinze, Peters, & Jancke, 2002; Larson, Haier, LaCasse, & Hazen, 1995; O'Boyle et al., 2005; Thomsen et al., 2000; Unterrainer, Wranek, Staffen, Gruber, & Ladurner, 2000; Weiss et al., 2003a,b). In case of equal experimental task performance, neural correlates of the capability-related group factor do not represent an NCP of the applied task (according to the above definition) but rather indicate unknown group-specific neurocognitive factors which are irrelevant with regard to experimental task performance (e.g. stress response).

Alternatively, studies on NCPs may focus more directly on the effects of behavioral performance in an experimental task on the brain activations which were elicited by this very task. Task

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performance effects on functional brain activation (and also connectivity) were repeatedly reported and actually challenge any too simplistic approach to functional brain mapping (Rypma et al., 2006; Tagaris et al., 1996b, 1997; Unterrainer et al., 2000, 2005). Evidently, this approach makes full use of the available behavioral and neurophysiological data obtained by functional neuroimaging. In addition, NCPs of a given task can be assessed in non-indicated standard subjects, for example by contrasting retrospectively identified high *vs.* low experimental task performers (Rypma et al., 2006).

In the present fMRI study, we combined these two research strategies to allow their evaluation and comparison. Referring to several previous studies from other groups (O'Boyle et al., 2005; Unterrainer et al., 2000, 2004, 2005), we simultaneously examined the effects of math talent, gender and experimental task performance on brain activations during mental rotation. Mental rotation is one of the best studied paradigms in both experimental psychology and cognitive neuroscience since its introduction by Shepard and Metzler (1971). On a behavioral level, both gender (Collins & Kimura, 1997; Kimura, 1996; Linn & Petersen, 1985; Lippa, Collaer, & Peters, 2010; Lubinski & Humphreys, 1990; Masters & Sanders, 1986, 1993; Moore & Johnson, 2008; Peters, 2008; Quinn & Liben, 2008; Voyer & Hou, 2006; Voyer, Voyer, & Bryden, 1995) and math talent (Casey, Nuttall, & Benbow, 1995; Hyde, 2005; O'Boyle, Benbow, & Alexander, 1995; Spelke, 2005) have shown reliable effects on mental rotation performance. Mental rotation reliably activates the posterior parietal cortices (PPC) which also play a key role for working memory and general intellectual functioning (Champod & Petrides, 2007, 2010; Jung & Haier, 2007; Zacks, 2008).

Unfolding the idea of specific neural mechanisms underlying better cognitive performance of a given task, we tested the following hypotheses:

(I) Mathematically gifted vs. control subjects and male vs. female subjects show better mental rotation performance.
(II) *Effect of the experimental task performance factor*: Activation of the PPC is obtained as an NCP, i.e. a positive neural correlate of mental rotation performance.
(III) *Effects of capability-related factors*: Math talent and gender yield activations of the PPC similar to the effects of experimental task performance as both are associated with better experimental task performance.
(IV) As the elicited neurocognitive activations are more inherently related to the experimental task, most of the variance of PPC activations can be explained by the experimental task performance factor.

2. Materials and methods

This study was approved by the Ethical Review Board of the Medical Faculty at the University of Bonn (No. 039/06). The study was carried out in accordance with *The Code of Ethics of the World Medical Association* (Declaration of Helsinki) for experiments involving humans.

2.1. Subjects

The study included 17 adolescent mathematically gifted subjects (MATH) and 20 same-aged control subjects (CON) between the ages of 15 and 18 without mathematical talent. Mathematical talent was assigned if the student was matriculated for Mathematics at the University of Bonn while attending high school (which relies on the recommendation of their schools) or if a subject recently participated in the 'Mathematical Olympiad' at a federal state level (state of North-Rhine Westphalia; total in 2007: $N = 350$ out of 16,000 participants on the community level). During subject recruitment, we additionally aimed at an equal distribution of male and female subjects in both samples to implement gender as an independent second capability-related group factor. Due to technical artifacts in the MRI data, three control subjects had to be excluded from the final analysis. Table 1 lists the characteristics of the included subjects. All subjects had normal or corrected-to-normal vision. Subjects were reimbursed for participation (10€/h) and travel costs. All subjects and their parents gave written informed consent according to the rules of good scientific practice.

2.2. Task

The original Shepard–Metzler (SM) paradigm shows a pair of drawings of quasi-3D-figures, each of which is constructed out of 10 cubes rendered in two dimensions ("3D figures") and requires a matching decision (identical vs. mirrored). In contrast, the Vandenberg–Kuse (VK) paradigm (Vandenberg & Kuse, 1978) which was applied in the majority of neuroimaging studies (Zacks, 2008) simultaneously shows one Shepard–Metzler figure as the target and four additional figures as probes and requires the subjects to select the one probe which matches the target though being spatially rotated (i.e. 4-alternatives forced choice; Peters & Battista, 2008; Peters et al., 1995). In this paradigm, identical stimuli (i.e. 0° angular disparity condition), scrambled dot patterns derived from the figures, or black and white bars serve as the control stimuli.

We propose a modified preparation rotation paradigm (Jansen-Osmann & Heil, 2007): (i) To avoid the reportedly high error rates (>40%) of established paradigms (O'Boyle et al., 2005; Weiss et al., 2003a,b); (ii) to separate mental rotation proper from both the encoding of the stimulus and the matching test; and (iii) to improve experimental control over the task difficulty in terms of both cognitive load and speed demands for future studies. The modified paradigm is shown in Fig. 2. A two-dimensional rendering of a three-dimensional stair-like figure composed of three cubes (i.e. a fragment of the original Shepard–Metzler items; Fig. 1) was used as the stimulus. Rotations of this object had to be performed at 90° (instead of 15°) angles within one of the three spatial planes (horizontal, sagittal, frontal) resulting in 12 possible positions of the object. At the beginning of each trial, the stimulus was presented for 2 s in a randomly selected position. Subjects were then prompted to perform four continuous mental rotations of the object starting from the initial position as indicated by four serially presented arrows (duration: 13 s, i.e. 3.25 s per rotation; each arrow presented for 0.813 s). Pilot studies in adolescent control subjects ($N = 30$) confirmed the appropriateness of these speed demands. In the task condition, the rotation plane was changed either for one time or for three times: In Fig. 2, the task condition shows three rotation plane changes (upward/sagittal, right/horizontal, clockwise/frontal, downward/sagittal). In the control condition (active low level task), the arrows indicated back-and-forth left and right rotating of the object within the horizontal plane (Fig. 2). The subjects were instructed that this condition only required the maintenance of the figure in its initial position. Each trial was completed by a matching decision task presenting the object in one of the twelve possible positions as a probe. Subjects pressed a button to indicate if the probe matched the figure's position after performing the instructed rotations (response latency: 3 s). A total of 30 control and 30 task trials were presented alternately allowing mental rotation-related brain activations to return to the baseline. Matching decisions were recorded as correct or false responses. The individual mental rotation accuracy score, *MRX*, was defined by *MRX* = (1 − (number of errors during task trials/number of task trials − number of errors during control trials/number of control trials)) which obtains a positive indicator of