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Neural efficiency in working memory tasks: The impact of task demand

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ABSTRACT

Studies of human intelligence provide strong evidence for the neural efficiency hypothesis, which suggests more efficient brain functioning (i.e., less or more focused activation) in more intelligent individuals. Recent studies have specified the scope of the neural efficiency hypothesis by suggesting that the relationship between brain activation and intelligence only holds true for problems of moderate difficulty and can be altered through training and is only found in frontal brain regions. We investigated the moderating roles of task difficulty and training on the neural efficiency phenomenon in the context of working memory (WM) training.

In two studies of 54 participants (study 1) and 29 participants (study 2), cortical activation was assessed by means of electroencephalography (EEG), or more precisely by means of event-related desynchronization (ERD) in the upper alpha band. ERD was assessed during the performance of WM tasks in a pre-test – training – post-test design, comparing groups of lower and higher intelligence.

We found supportive evidence for the neural efficiency hypothesis only in moderately difficult WM tasks in frontal brain regions, even in the absence of performance differences. There was no effect of intelligence on the simple or highly demanding, adaptive WM tasks. In the latter task, however, an intelligence-related difference emerged at the behavioral level, but training did not modulate the relationship between intelligence and brain activation.

These results corroborate the moderating role of task difficulty in the neural efficiency hypothesis in the context of WM demands and suggest that training does not impact the neural efficiency phenomenon in the context of WM demands.

1. Theoretical background

According to the neural efficiency hypothesis, differences in intelligence become apparent in the degree of brain activation that occurs during problem solving, i.e., for more intelligent individuals, the correct answer comes with less brain activation than for less intelligent individuals (Haier et al., 1988). This original hypothesis of neural efficiency was introduced in a positron emission tomography (PET) study, the results of which showed less brain glucose metabolism in more intelligent individuals while solving cognitive tasks. Haier and colleagues stated, “Intelligence is not a function of how hard the brain works but rather how efficiently it works … This efficiency may derive from the disuse of many brain areas irrelevant for good task performance as well as the more focused use of specific task-relevant areas” (Haier, Siegel, Tang, Abel, & Buchsbaum, 1992b, pp. 415–416). In addition, with electroencephalography (EEG), it was shown that event-related desynchronization (ERD) in the upper alpha band, considered an index of cortical activation (Klimesch, Doppelmayr, Pachinger, & Ripper, 1997; Pfurtscheller & Aranibar, 1977), is negatively related to intelligence (for a review, cf. Neubauer & Fink, 2009). However, although the

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neural efficiency hypothesis has often been confirmed, moderating factors have been identified, in particular, task difficulty and practice or learning (Neubauer & Fink, 2009).

Various studies have demonstrated that the relationship between neural efficiency and intelligence may be altered by task difficulty (for an overview, see Neubauer & Fink, 2009). For instance, Neubauer, Sange, and Pfurtscheller (1999) did not find differences in brain activation between individuals with higher and lower IQ for simple (i.e., elementary cognitive) problems. The authors therefore concluded that a certain level of task difficulty is required for a corroboration of the neural efficiency effect. A different picture emerged in a study EEG measures while solving the Advanced Progressive Matrices Test (RAPM; Raven, 1990). Specifically, a negative relation between brain activation and intelligence was found for the easier items only, while for the more difficult ones, the opposite relationship was observed (Doppelmayr et al., 2005a). According to Neubauer and Fink (2009), these results do not necessarily contradict each other. The authors conclude, rather, that when more effort is required, more intelligent participants invest their available resources, resulting in both higher cortical activation and better achievement. Thus, it seems that in complex tasks, more intelligent individuals invest more cortical resources, resulting in a positive correlation between cortical activation and performance. In contrast, for moderate tasks, more intelligent individuals require less cortical resources to achieve the same performance as less intelligent individuals, resulting in a negative relation between cortical activation and performance.

Individual task difficulty, however, can be altered by practice, and based on the neural efficiency hypothesis, practice-related changes in brain activation may also be a function of intelligence. This has, in fact, been confirmed in two studies, which found a stronger decrease in activation after training for individuals with higher intelligence (Haier et al., 1992b; Neubauer, Grabner, Freudenthaler, Beckmann, & Guthke, 2004). The role of practice in the neural efficiency phenomenon has also become salient in investigations of experts in different domains who had achieved their expertise level through long-term training (Grabner, Neubauer, & Stern, 2006; Grabner, Stern, & Neubauer, 2003). These studies revealed that neural efficiency (in terms of more focused brain activation) is a function not only of intelligence but also of expertise. For instance, Grabner et al. (2006) compared the brain activation of individuals with lower and higher intelligence as well as with lower and higher expertise in tournament chess while solving chess-related tasks. They found independent impacts of intelligence and expertise level on brain activation. As expected, brighter individuals (independently of their expertise) displayed lower overall brain activity than their less intelligent peers. In addition, experts showed a lower frontal and more focused brain activation pattern compared to novices (i.e., individuals with lower degree of expertise).

Also with regard to brain areas only partial support for the neural efficiency hypothesis has been found. Neubauer and Fink (2009) summarize that effects of neural efficiency, i.e. the expected negative brain–intelligence relationship has been observed for frontal (but not for parietal) brain areas. For instance, Neubauer et al. (2004) found the strongest intelligence-related differences during reasoning tasks in frontal areas, more specifically in the prefrontal cortex, an area most strongly associated with reasoning processes. Similarly, Gray, Chabris, and Braver (2003) reported that for WM tasks prefrontal cortical activation discriminates between subjects with higher and lower intelligence, which is in accordance with findings of a high involvement of frontal areas while solving WM tasks (Smith & Jonides, 1997). A discrepancy between frontal and parietal brain areas in the context of neural efficiency has also been revealed in three studies which reported less frontal activation for more intelligent participants and a tendency for more parietal activation in the same participants (Gevins & Smith, 2000; Jaušovec & Jaušovec, 2004 and Rypma et al., 2006). Thus, even though an interplay of frontal and parietal brain areas is discussed to be important for intelligence (cf. the parieto-frontal integration theory by Jung & Haier, 2007); neural efficiency in terms of a negative brain–intelligence relationship has predominantly been found in frontal brain regions.

To summarize, several studies have provided support for the neural efficiency hypothesis mainly for frontal brain areas, but have also shown that task difficulty and training can moderate the relationship between intelligence and brain activation. There is, however, a paucity of studies in which task difficulty and training were combined in a comprehensive design. We conducted such a study involving WM training.

There is a wide agreement that WM is a core of human intelligence. Numerous studies have demonstrated substantial correlations between achievement on WM tasks and IQ (e.g., Conway, Cowan, Bunting, Therriault, & Minkoff, 2002; Conway, Kane, & Engle, 2003; Engle, Tuholski, Laughlin, & Conway, 1999; Kane et al., 2004; Kyllonen & Christal, 1990). It can therefore be expected that the use of brain imaging while solving WM tasks will particularly highlight the impact of intelligence on neural activation. Moreover, the difficulty of WM tasks can be varied in a systematic and transparent way, for instance, by modulating demands for interference resolution or the amount of load. This allows the study of how the relationship between brain activation and intelligence may be moderated by task difficulty. Lastly, there is overwhelming evidence for the trainability of many types of WM tasks. As a result of repeated practice, the solution rate increases while the solution time goes down. Whether training effects transfer to other WM tasks, thereby demonstrating the malleability of WM functions, is hotly debated in psychology, and reviews and meta-analyses have provided reasons to doubt broader transfer effects (Chein & Morrison, 2010; Melby-Lervåg & Hulme, 2013; Shipstead, Redick, & Engle, 2012). Taken together, the advantages of WM tasks in investigations of neural efficiency are threefold: First, WM is seen as a basis of human intelligence. Second, the difficulty level can be manipulated gradually in that more or less WM load is incorporated into tasks. Third, WM activities are well represented in cortical activation, i.e., it is known that while solving WM tasks, there is a high involvement of frontal areas (Smith & Jonides, 1997). The present study consists of two training studies in which we assess brain activation (in terms of alpha ERD) in frontal areas before and after a three-week WM training in adult students differing in intelligence. The two studies differ in the level of task difficulty or WM load.

In study 1, we administered a WM-training with moderate complexity focusing on interference resolution. Interference resolution, which is the ability to select information among competing alternatives, is seen as a key function of WM (e.g., Nee, Wager, & Jonides, 2007). Specifically, the participants in the interference group (i.e., experimental group) practiced