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The role of fluid intelligence and learning in analogical reasoning: How to become neurally efficient?

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ABSTRACT

This study on analogical reasoning evaluates the impact of fluid intelligence on adaptive changes in neural efficiency over the course of an experiment and specifies the underlying cognitive processes. Grade 10 students ($N = 80$) solved unfamiliar geometric analogy tasks of varying difficulty. Neural efficiency was measured by the event-related desynchronization (ERD) in the alpha band, an indicator of cortical activity. Neural efficiency was defined as a low amount of cortical activity accompanying high performance during problem-solving. Students solved the tasks faster and more accurately the higher their FI was. Moreover, while high FI led to greater cortical activity in the first half of the experiment, high FI was associated with a neurally more efficient processing (i.e., better performance but same amount of cortical activity) in the second half of the experiment. Performance in difficult tasks improved over the course of the experiment for all students while neural efficiency increased for students with higher but decreased for students with lower fluid intelligence. Based on analyses of the alpha sub-bands, we argue that high fluid intelligence was associated with a stronger investment of attentional resource in the integration of information and the encoding of relations in this unfamiliar task in the first half of the experiment (lower-2 alpha band). Students with lower fluid intelligence seem to adapt their applied strategies over the course of the experiment (i.e., focusing on task-relevant information; lower-1 alpha band). Thus, the initially lower cortical activity and its increase in students with lower fluid intelligence might reflect the overcoming of mental overload that was present in the first half of the experiment.

1. Introduction

Analogical reasoning is an essential cognitive process in problem solving (Hofstadter, 2001). When we speak of analogical reasoning, we are referring to the process of transferring information from a source domain (A:A′) to a target domain (B:B′) based on analogical similarities between the two. Analogical reasoning involves several sub-processes such as (1) building representations of the structures A, A′, B, and B′, (2) selecting relevant and inhibiting irrelevant features, and identifying relations in the source pair (A:A′), (3) mapping or transferring relations between source and target (B:B′) pair, and (4) evaluating the analogy (Gentner, 1983; Holyoak & Morrison, 2005; Kokinov & French, 2003; Mulholland, Pellegrino, & Glaser, 1980; van der Meer, 1996). Individual differences in executing these sub-processes might cause performance differences in analogical reasoning. Intelligence is known to be one factor affecting performance on diverse analogical reasoning tasks (Hofstadter, 2001; Prabhakaran, Smith, Desmond, Glover, & Gabrieli, 1997; Vakil, Lifshitz, Tzuriel, Weiss, & Arzuoan, 2011). One approach to investigate sources of individual differences in cognitive processing is the analysis of the neural efficiency (Haier et al., 1988), which will be the focus of the present study.

1.1. The relationship between intelligence and neural efficiency

Neurally efficient processing is characterized by high performance, that is, short response times (RT) and high accuracy, and low brain activity levels. However, there is a critical debate as to whether high performance, usually found in highly intelligent individuals, is associated with low or high brain activity. Various studies suggest that neural efficiency is highest in easy and familiar tasks (i.e., participants would show a high performance with low

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brain activity), while this pattern does not hold for difficult and novel tasks. Further, it seems to concern only specific brain regions, which in turn depend on the specific task (for review, see Neubauer & Fink, 2009).

Regarding analogical reasoning, Doppelmayr, Klimesch, Hodlmoser, Sauseng, and Gruber (2005), for instance, investigated neural mechanisms underlying intelligence-related differences in solving semantic analogy tasks. They showed that more intelligent individuals exhibited greater left-hemispheric cortical activity while solving the task more accurately than less intelligent individuals (i.e., *no* neurally efficient processing as per its definition). Cortical activity was measured by the event-related desynchronization (ERD) in the upper alpha band of the electroencephalogram (EEG). The alpha ERD indicates cortical activity (Klimesch, 1999) and the upper alpha band (ca. 11–13 Hz) is linked with semantic memory (Klimesch, Schimke, & Schwaiger, 1994). Thus, the larger ERD was interpreted as a stronger activation of the semantic processing system in individuals with higher intelligence. Despite semantic processing, other processes in reasoning might be affected by intelligence as well. The present study addresses intelligence-related differences in neural efficiency indicating differences in the above mentioned analogical reasoning processes (e.g., selecting relevant and inhibiting irrelevant features).

1.2. The neural mechanisms of analogical reasoning and their relation to FI

Particularly fluid intelligence (FI; Cattell, 1987) is highly related to reasoning abilities like solving unfamiliar problems by selecting relevant and inhibiting irrelevant information, identifying complex relations, and being flexible (Hofstadter, 1995; Holyoak & Thagard, 1995; van der Meer, 1996). We can investigate FI-related differences in the processes involved in reasoning best by means of unfamiliar geometric analogical reasoning tasks (Hosenfeld, Van den Boom, & Resing, 1997). In this regard, only a little research on the neural mechanisms of solving such tasks has been accomplished so far.

Neuroimaging and stimulation studies have shown that geometric analogical reasoning involves a network of (left) frontal, parietal, inferior temporal, and occipital brain regions (Boroojerdi et al., 2001; Preusse, van der Meer, Deshpande, Krueger, & Wartenburger, 2011; Preusse et al., 2010; Wartenburger, Heekeren, Preusse, Kramer, & van der Meer, 2009; Watson & Chatterjee, 2012; Wharton et al., 2000) with these regions becoming more activated when task demands increase (e.g., Preusse et al., 2010). Moreover, Krawczyk et al. (2010) found decreased performance in a picture analogy task among adolescents with lesions due to traumatic brain injuries (TBI) in those regions that are assumed to be relevant for analogical reasoning (i.e., frontal, temporal, parietal, occipital, basal ganglia, corpus callosum). The performance deficit was especially apparent in tasks with a high relational complexity and distracting information, indicating that individuals with TBI did not execute the task-relevant cognitive processes in a sufficient way. In healthy participants, Sweis, Bharani, and Morrison (2012) used an event-related potential (ERP) approach to investigate influencing factors on inhibitory control processes during analogical reasoning. In their study, ERPs indicated that more information entered visuospatial working memory (WM) in individuals with a low WM span than in those with a high WM span, probably due to an inferior inhibition of task-irrelevant information.

Van der Meer et al. (2010) investigated FI-related differences in neural efficiency during the processing of a geometric analogy task. Here, students with high FI performed better (faster and more accurately) than students with average FI. In addition, they exhibited greater peak pupil dilation, an aggregate measure of cognitive load (Beatty & Lucero-Wagoner, 2000), especially in difficult tasks. These findings are contrary to the neural efficiency hypothesis. To analyze the impact of FI on neural efficiency during analogical reasoning in more detail, Preusse et al. (2011) conducted an fMRI study using the same geometric analogy task. They showed that high FI is associated with greater activation of parieto-occipital regions compared to average FI. By contrast, lower activation indicating more efficient processing was found in frontal brain regions. This finding is consistent with the findings of several other studies on FI-related differences in neural efficiency (Jaušovec & Jaušovec, 2004; Rypma et al., 2006).

However, Preusse et al. (2011) trained their participants in the analogy task one month prior to the examination. Learning is a well-established factor that influences neural efficiency (for review, see Neubauer & Fink, 2009). Moreover, previous studies have shown that the impact of learning differs for individuals with higher and lower FI, with stronger activity decreases in individuals with high FI (Haier, Siegel, Tang, Abel, & Buchsbaum, 1992; Neubauer, Grabner, Freudenthaler, Beckmann, & Guthke, 2004). The present study accounts for the impact of learning on neural efficiency and its interaction with FI.

1.3. The role of learning for neural efficiency in analogical reasoning

It has been assumed that learning leads to the development of more efficient cognitive strategies, which results in less WM demands and lower brain activity (Haier, Siegel, MacLachlan, et al., 1992). However, past research has revealed inconsistencies concerning the decreases and increases in regional brain activation during learning. Consequently, Kelly and Garavan (2005) inferred that learning results in a redistribution (activity increases in some areas, but decreases in others) or reorganization (change of the activation location) of brain activity. In an fMRI study, Wartenburger et al. (2009) investigated the effect of short-term learning during a geometric analogy task. They found improvements in performance and, in difficult tasks, a decrease in activity in the parietal and inferior temporal (but not frontal) brain regions over the course of the experiment. This decrease was interpreted as an increase in neural efficiency or automaticity due to training.

However, Wartenburger et al. (2009) did not take into account training effects for different levels of FI. According to Blair (2006), learning effects are stronger the higher the FI is, thus, resulting in a stronger decrease of WM resources required for problem-solving (see also Haier, Siegel, Tang, et al., 1992). In addition, subjects in the study by Wartenburger et al. (2009) were highly familiar with the task due to their participation in a similar experiment two months prior to the investigation. Therefore, the first learning-related adaptive changes in strategy use and related brain activity might have already had occurred. Aside from that, the impact of FI on learning should be especially high in early learning phases, particularly in hard tasks, since resources from WM are of greater importance for that stage than after an extensive training (Ackerman, 1987, 1988).

In a one-year follow-up study by Preusse et al. (2010) addressing long-term learning effects in analogical reasoning, the authors also considered participants' FI. In this study, a geometric analogy task was presented only to students with high FI. At the second time point, the same frontoparietal network was involved in the problem-solving process as during the first time point one year before. Despite the fact that participants were already familiar with the task at the first time point, a further improvement in performance indicated by faster responses at the second time point was observed. The authors took this as evidence for a further increase in neural efficiency in the entire frontoparietal network due to long-term cognitive development and educational progress. However, the brain activity changes over time in individuals with high FI were not compared to changes in individuals with lower