From neural oscillations to reasoning ability: Simulating the effect of the theta-to-gamma cycle length ratio on individual scores in a figural analogy test ☆

Adam Chuderski [a],*, Krzysztof Andrelczyk [b]

[a] Cognitive Science Department, Institute of Philosophy, Jagiellonian University, Grodzka 52, 31-044 Krakow, Poland
[b] Institute of Psychology, Jagiellonian University, Mickiewicza 3, 31-120 Krakow, Poland

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ABSTRACT

Several existing computational models of working memory (WM) have predicted a positive relationship (later confirmed empirically) between WM capacity and the individual ratio of theta to gamma oscillatory band lengths. These models assume that each gamma cycle represents one WM object (e.g., a binding of its features), whereas the theta cycle integrates such objects into the maintained list. As WM capacity strongly predicts reasoning, it might be expected that this ratio also predicts performance in reasoning tasks. However, no computational model has yet explained how the differences in the theta-to-gamma ratio found among adult individuals might contribute to their scores on a reasoning test. Here, we propose a novel model of how WM capacity constrains figural analogical reasoning, aimed at explaining inter-individual differences in reasoning scores in terms of the characteristics of oscillatory patterns in the brain. In the model, the gamma cycle encodes the bindings between objects/features and the roles they play in the relations processed. Asynchrony between consecutive gamma cycles results from lateral inhibition between oscillating bindings. Computer simulations showed that achieving the highest WM capacity required reaching the optimal level of inhibition. When too strong, this inhibition eliminated some bindings from WM, whereas, when inhibition was too weak, the bindings became

☆ The code of the oscillatory model may be downloaded from the following webpage: http://student.phils.uj.edu.pl/kogniwiki/en:zaklad:adam_chuderski.

* Corresponding author.
  E-mail address: adam.chuderski@gmail.com (A. Chuderski).

unstable and fell apart or became improperly grouped. The model aptly replicated several empirical effects and the distribution of individual scores, as well as the patterns of correlations found in the 100-people sample attempting the same reasoning task. Most importantly, the model's reasoning performance strongly depended on its theta-to-gamma ratio in same way as the performance of human participants depended on their WM capacity. The data suggest that proper regulation of oscillations in the theta and gamma bands may be crucial for both high WM capacity and effective complex cognition.

1. Introduction

One of the most profound findings regarding human complex cognition (i.e., reasoning, planning, problem solving, creativity, language use etc.) consists of the observation that, on one hand, the level of cognitive abilities in an individual is highly stable (diverse abilities strongly correlate; Deary, 2012), whereas on the other hand one can find enormous differences in cognitive ability within the population, ranging from people who significantly broaden our science, technology, and arts, to those who hardly cope with even the simplest cognitive tasks. For the last fifty years, these two observations have motivated intensive research on the two resulting problems: (a) is there a general (neuro)cognitive mechanism that generally determines the effectiveness of human complex cognition, making various complex tasks mutually correlate – the phenomenon called (general) fluid intelligence, or (fluid) reasoning ability (Gustaffson, 1984), and (b) why – if such a core mechanism exists – do people differ so much in its capability? In other words, what prevents humans from possessing the maximum possible level of that capability, in analogy to perceptual processes that are nearly optimal in almost all healthy people?

One category of findings regarding the low-level mechanisms that can determine reasoning ability consists of neuroanatomical explanations. For example, more intelligent people possess slightly larger brains, probably resulting from a larger size of frontal/parietal structures important for cognition (Jung & Haier, 2007), and more gray (more neurons) or white matter (more inter-neuron connections) in the brain (Neubauer & Fink, 2009). Other researchers do not believe that the sheer amount of brain material matters for reasoning ability; instead they look for factors that affect how well such material can function. To use an analogy, the largest computer will not be efficient if it has a poor operating system. Consequently, more intelligent brains have been shown to be faster (Jensen, 1998), more reliable (e.g., in some conditions generate less noisy EEG data; Lutzenberger, Birbaumer, Flor, Rockstroh, & Elbert, 1992), and more metabolically efficient (Neubauer & Fink, 2009). Also, more extensive connectivity and communication between neural structures has been demonstrated in people of higher ability (Cole, Yarkoni, Repovs, Anticevic, & Braver, 2012).

However, the results cited above have yielded two substantial problems for the explanation of mechanisms that determine reasoning ability. First, if one looks for cortical structures whose size, activity, efficiency or connectivity may predict reasoning ability, there are really few structures which *do not* predict it (primarily early occipital and some mid-brain structures; see Colom et al., 2009). This may suggest that what is important for reasoning ability level is not a specific function of one or several brain loci, but some global mechanisms resulting from interaction among various brain areas. Second, all discussed factors yielded quite weak correlations with reasoning tasks, usually around $r = .30$, but rarely surpassing $r = .50$, so they leave 75–90% of reasoning variance unexplained.

At the same time in cognitive psychology, a mechanism called *working memory* (WM), that is responsible for the maintenance and transformation of information in the service of the current goal/task (Cowan, 2001), has been shown to very strongly correlate with complex cognitive tasks, explaining at least 50% of their variance (Kane, Hambrick, & Conway, 2005) up to almost total variance