The neural dynamics of problem-solving are associated with computational complexity

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Every day, humans face decisions requiring them to solve complex problems, many of which are computationally intractable. Examples of tasks that involve solving intractable problems include attention gating, task scheduling, shopping, routing, bin packing, and game play.

Despite the relevance of computationally complex problems in daily life, little is known about the neural processes and dynamics that underlie how people solve these problems. Complex problems usually require exploring a vast search space to find a solution and require an extended period of time to solve. These two characteristics make the study of these problems particularly challenging. Explicitly, the diversity in strategies, together with the extended period of time required to execute these strategies, could entail markedly different neural dynamics. It is unclear how to characterize the invariants of these dynamics across people and even across particular cases of the problem.

In this study, we put forward a method that provides a way to address this issue by characterizing neural invariants of problem-solving by mapping intrinsic properties of problems to neural dynamics. Specifically, we propose that computational complexity theory can be used to characterize features of problems that could help identify generic neural markers associated with computational hardness and reliability of a solution during problem-solving.

Here we investigate the neural correlates of computational hardness and reliability in the knapsack decision problem and explore the related neural dynamics (Figure 1). To this end, we performed an experiment in which participants solved several instances of the knapsack decision problem while undergoing fMRI. Critically, in order to be able to investigate the temporal dynamics of problem-solving at a more granular level, we employed an ultra-high field scanner for this study. This allowed us to increase both the temporal and spatial resolution of the neuroimaging data collected.

We first replicated previous behavioural results. We show that the task-independent metrics of complexity do affect decision quality. Participants spend more time on instances with higher complexity and perform worse on these instances. When considering the neural correlates of computational hardness, we find that they overlap with those associated with the multiple demand system (MDS). Importantly, our results show that these vary throughout the different stages of the task, supporting the premise that the MDS is a heterogeneous set of regions that play a dynamic and varying role at different stages in problem-solving. Of note, in line with our conjecture, we found neural markers of the reliability of a solution in the cingulo-opercular network. These overlap with regions associated with neural markers of uncertainty in probabilistic tasks.

Additionally, in order to investigate the inter-region neural dynamics, we investigated how the functional connectivity between regions of interest in the MDS changed during problem-solving. We found, in line with our hypothesis, that during the solving stage of the task, connectivity patterns changed. However, contrary to our expectations, we found no significant effect of hardness nor reliability on the strength of this connectivity.

Overall, our results extend previous findings on the neural underpinnings of problem-solving by providing a framework for the study of intractable problems using generic definitions of computational hardness and reliability. Finally, our findings complement the investigation of cognitive control by providing a framework to study cognitive requirements in a task-independent way.

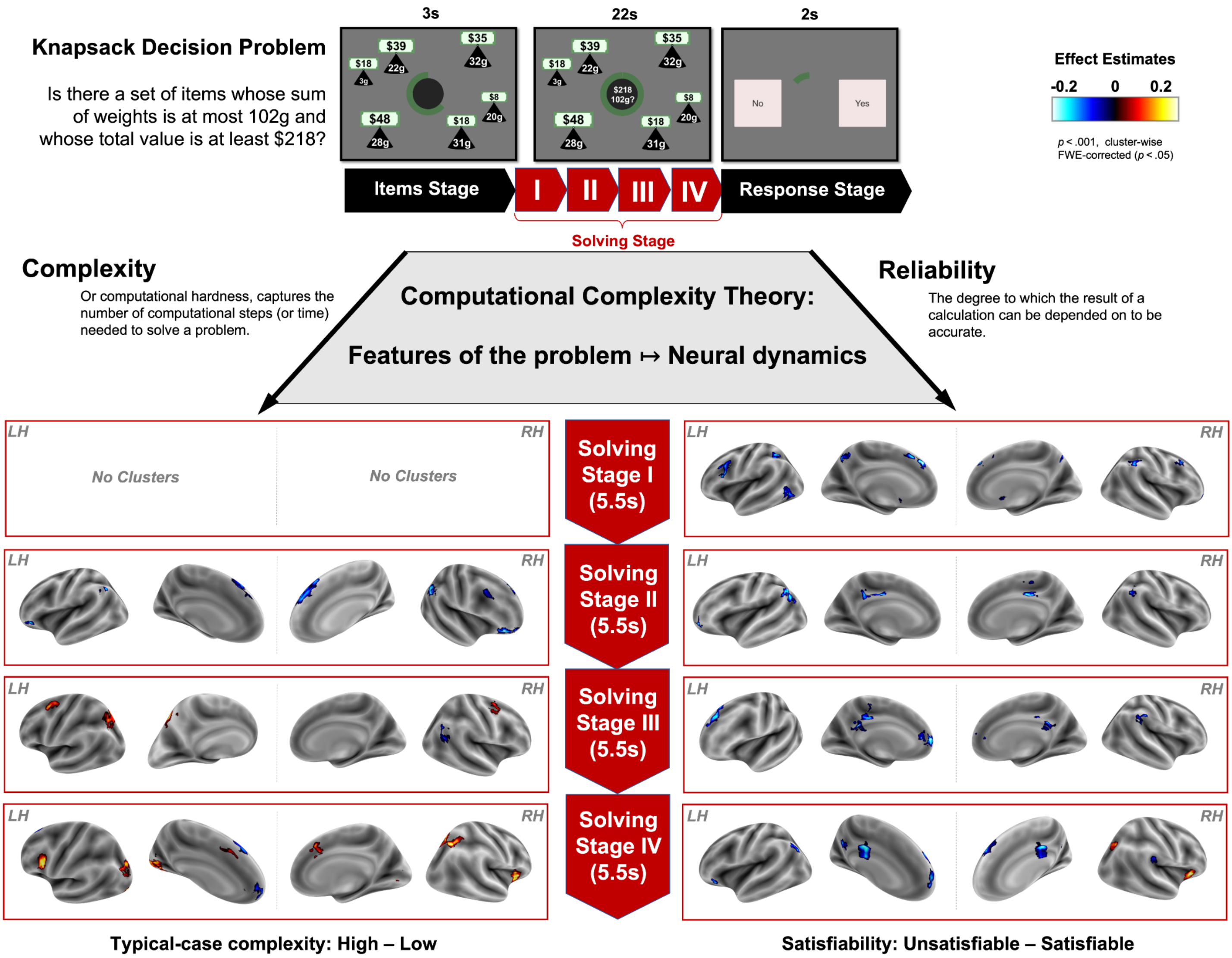

Figure 1. Neural correlates of computational hardness and reliability during problem-solving. Experimental paradigm and main results.