# Locating the Problem Representation Bottleneck in the Brain

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## The Problem Representation Bottleneck

In their theory of multitasking, Threaded Cognition, Salvucci and Taatgen (2008) presented evidence for two central cognitive bottlenecks: declarative memory and procedural memory. However, in combination with ACT-R (Anderson, 2007), Threaded Cognition suggests a third resource that can act as a bottleneck: the problem representation resource. The problem representation resource is used for mentally maintaining information that is necessary for performing a task. This information is typically not present in the world and often constitutes an intermediate solution to a problem. For instance, if one has to solve a problem like $2x + 5 = 10$, the intermediate step, $2x = 5$, would be stored as the problem representation (e.g., Anderson, 2007). According to ACT-R, the problem representation resource (the imaginal buffer) can hold only one piece of information concurrently. This would mean that if two tasks need to use the problem representation resource at the same time, this would result in interference. In two experiments we have shown that the problem representation indeed acts as a cognitive bottleneck (Borst & Taatgen, 2007; Borst, Taatgen, & Van Rijn, submitted). Cognitive models were developed to account for these results, showing that a problem representation bottleneck can indeed explain the human data.

In the current research, we used functional Magnetic Resonance Imaging (fMRI) to test our model of the problem representation bottleneck further. First, we let our existing ACT-R model make a priori brain activation predictions. Afterwards we tested these predictions in the scanner.

## Experiment & Model Predictions

The experiment existed of two tasks that had to be performed concurrently: subtraction and text entry. Both tasks were presented in two versions: an easy version in which maintaining a problem representation was not required and a hard version in which it was. The behavioral data shows a significant interaction effect of subtraction difficulty and text entry difficulty on the reaction times, comparable to the results in Borst et al. (submitted).

We used our existing model of the task to generate brain activation predictions. Basically, when an ACT-R module is active, it will produce a hemodynamic response in the brain region associated with it (for details, see Anderson, 2007). As the model explains the interference effects by using a problem representation bottleneck, we were most interested in the left parietal cortex (Talairach coordinates $x = -23$, $y = -64$, $z = 34$), the region associated with the problem representation resource (Anderson, 2007). The model predicted a strong interaction effect in this region: no activity in the easy subtraction / easy text entry condition, some activation in the easy/hard and hard/easy conditions (the problem representation is then involved in one of the tasks), and very strong activation in the hard/hard condition (the problem representation has to be swapped out constantly, see Borst et al., submitted). The model also predicted activation in five other important regions.

## Results

With respect to the problem representation resource, the results were mixed. First of all, the raw fMRI data does not show the predicted interaction effect. The main reason for this is that in the easy/easy condition – where no activation was predicted – we did find high activation levels. However, the problem representation region is known to follow activation in the fusiform gyrus (associated with the visual module in ACT-R). If we discount the visual part of the activation in the problem representation region, so that the activation in the easy/easy condition approaches 0, the activation is reasonably similar to our a priori model predictions ($R^2 = .64$).

Of the other five regions, the visual, motor and goal areas showed a reasonably good fit. The procedural area was hard to interpret, that is, we did not have strong predictions, and the results are not showing clear effects either. The prefrontal cortex (declarative memory) shows two groups of results: 4 participants showed negative activation, unlike our model, the other 5 participants showed positive activation, showing a similar pattern as the model ($R^2 = .76$).

## References

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