Concurrent multitasking

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CHAPTER 6

Summary and Conclusions

Where we summarize the findings of this dissertation and discuss the implications.

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A fundamental question about multitasking behavior is how the brain manages to perform multiple tasks concurrently. Several answers are possible. There might be a special multitasking center in our brains that is tasked to manage how multiple tasks are executed at the same time (Baddeley, 1986; Miller & Cohen, 2001). Multitasking may also be strategic in nature: each task combination requires learning a specific control strategy that prescribes how they should be performed concurrently (Meyer & Kieras, 1997). These strategies are likely to vary from person to person (Howes, Lewis, & Vera, 2009). Finally, it could be a distributed architecture where a simple scheduling mechanism uses the availability of the various cognitive resources to determine how task processes are interleaved (Salvucci & Taatgen, 2008). This would mean that cognitive mechanism that makes multitasking possible should be similar across the population. These different views are not necessarily mutually exclusive: how people multitask could be a combination of these ideas. In this thesis our starting assumption was that multitasking performance is the result of a distributed architecture in the brain. We examined how well this assumption fit the observed data, and how the other possible explanations play a role.

According to the architectural view, when two tasks require the same cognitive or peripheral function (i.e., vision, hearing, memory, or motor control) those tasks are said to overlap for that function. Overlap between tasks is likely to lead to interference, as only one task can use any of these functions at any given time due to the way the brain processes information. Interference between tasks will affect how (well) the tasks are performed. We found evidence for a distributed architecture of multitasking at several levels of description: it can be seen at the neurological and cognitive levels (Chapter 2 and Chapter 3), in resulting behavior (Chapter 4), and can even be observed in the combinations of tasks that people decide to perform concurrently (Chapter 5). These results imply that multitasking only has negative consequences. However, we show that is some cases multitasking can be beneficial to performance (Chapter 4). In the remainder of this chapter I will summarize our main results, and discuss the implications of our findings.

The Neural Basis of Concurrent Multitasking

In Chapter 2 we examined the brain activation patterns that occur during concurrent multitasking. There were several questions that we addressed: Is there a multitasking center in the brain? How can we explain the different patterns observed in previous multitasking neuroimaging data? And finally, can we use brain activation data of tasks to predict how well people perform when these tasks are performed concurrently? To that end we used a multitasking paradigm with three different tasks that are presented either individually, or in pairs of two. Thus, there were a total of six different conditions: three single tasks and three dual tasks. The tasks were selected to vary in the resources they required in order to be performed. In short, one task used visual and working-memory resources, one used aural and working-memory resources, and the last one used visual and manual resources. The overlap in resources required by each task was expected to lead to three different expressions of interference in the dual-task conditions: working-memory interference, visual interference, or no interference. We asked participants to perform these tasks in an fMRI scanner to measure their brain activity.

We found that the similarity between brain activity patterns of single-tasks was indeed predictive of the decrease in performance when those tasks were performed concurrently. As more similarity in the patterns means more similarity in the brain regions that are active, this indicates that task interference during multitasking is at least partially due to overlap in the resources used by each task. In line with this, we found no evidence of a multitasking-specific brain region, such as inferred previously (Collette et al., 2005; Dux, Ivanoff, Asplund, & Marois, 2006; Herath, Klingberg, Young, Amunts, & Roland, 2001; Szameitat, Lepsien, von Cramon, Sterr, & Schubert, 2006; Wu, Liu, Hallett, Zheng, & Chan, 2013).

This suggests that the interpretation of these data contradicts a number of earlier studies. However, we are able explain why some studies attribute their results to a multitasking center. We argue that the brain activity found to indicate a specialized multitasking area is caused by an interaction between tasks. Interactions between tasks can lead to a total of three different types of activity, which were all found in our data. Firstly, the activity in the dual task can be less than the sum of both single tasks (Just, Keller, & Cynkar, 2008). This occurs when tasks have to share time and resources. Secondly, the activity can be equal to the sum (Adcock, Constable, Gore, & Goldman-Rakic, 2000). This happens when tasks do not have to share: both can use resources they require within the time that is given. Finally, the activity can be more than the sum (Szameitat, Schubert, Müller, & Von Cramon, 2002). This indicates that additional processes are required for the dual task that are not part of the individual tasks. An example of this would be switching visual attention between two tasks. The activation caused by this third type of task interaction can be mistaken as evidence for a multitasking-specific area, as the activity of these processes is not present in the neuroimaging data of either individual task. In conclusion, all the neuroimaging data point towards multitasking being largely defined by a distributed architecture: task overlap was predictive for dual-task performance, and no multitasking center was found. Furthermore, neural activity found during multitasking can be explained by looking at the time and resource requirements of tasks.

Modeling Concurrent Multitasking

While the neuroimaging data helps us understand how multitasking manifests itself in terms of brain activity, it does not directly tell us what mechanisms cause this neural activation. One important mechanism that we still know relatively little about in terms of multitasking is working memory. Does working memory as it is used during concurrent multitasking behave as a singular system, or several systems that work together? An example of a singular system would be a small storage space containing a set of items that are immediately available for any sort of processing. When not present in this small storage, items need to be retrieved from long-term memory before they can be operated upon (see also: Altmann & Trafton, 2002; Meyer & Kieras, 1997; Salvucci & Taatgen, 2008). An example of a multi-component system might have a storage space that can contain and operate upon only a single information item. This concept is sometimes referred to as a focus of attention (see also: Lewis-Peacock, Drysdale, Oberauer, & Postle, 2012; Oberauer, 2002; Unsworth & Engle, 2007). Quick access to other items can be achieved by keeping them active in long-term memory, which would be achieved by introducing a rehearsal loop to the system. Essentially, when compared to the single-component system this multi-component system separates the item being operated upon from the total set of task relevant items being maintained. We built cognitive models of both the single and multi-component working-memory systems, and tested them against two data sets. The first data set contained behavioral data from the paradigm detailed in Chapter 2, while the second dataset contained both behavioral and neuroimaging data of that same paradigm. To reiterate, in this paradigm participants performed each of the three tasks in isolation, as well as all three combinations of these tasks.

The model that used a single-component working-memory was used to generate predictions of behavioral data and neural activity in certain brain regions. These regions were related to the cognitive resources required to perform the tasks in the paradigm. While the model could predict the behavioral data quite well, it failed to reproduce the neural activity observed in the second data set. The multi-component working-memory model was able to reproduce the behavioral data of both sets as well as the neuroimaging data, and argues that the singular model view is not correct. Instead it shows that the interference caused by two tasks requiring working memory at the same time is the result of interactions between several resources, instead of contention for a single system. This has consequences for the way we think about working memory in multitasking research: If working memory is not a single system, then its individual parts can work in parallel.

The multi-component model shows that some strategic control is required to use working memory during concurrent multitasking: when these parts become available again is determined by the task currently using it. Additionally, the particular parts of working memory that are used will depend on the particular task being performed. Together these findings indicate that predicting how working memory interference affects multitasking performance is more complicated than previously assumed. The fit of the multi-component model to the data supports the results of the neuroimaging study in that multitasking is primarily implemented as a distributed architecture. However, there also seem to be strategic components to multitasking. As indicated by working memory, it is possible to manage the availability of resources on a strategic level, overriding the default possession and release mechanisms. Perhaps a single strategic procedure could even string the use of several resources together, only releasing them for use by another task when the procedure finishes as a whole.

Driving Performance When Multitasking

Driving is another task that shows how difficult it can be to predict multitasking performance: researchers have shown that in some circumstances driving performance will *improve* when concurrently performing a second task (Atchley & Chan, 2010; Gershon, Ronen, Oron-Gilad, & Shinar, 2009). As an extension of these previous studies we created a simulated driving paradigm that allowed us to examine the effect of a variety of secondary tasks on driving, under different traffic situations. The purpose of this experiment was to illuminate under what conditions secondary activities might be beneficial to driving. Four secondary task conditions were used: driving without an extra task, passively listening to a talk show while driving, listening to segments of a talk show and answering a multiple-choice question for every segment, and finally reading transcript segments of a talk show on a tablet and answering a multiple-choice question for each. Thus, every condition taxed drivers in a different way in terms of working-memory, peripheral, and motor resources. Two traffic scenarios were tested: one with no traffic in the driver's lane, and one where some traffic needed to be overtaken. Driving was a low-workload task when the right lane was empty, as it only required the driver to maintain a safe position in the lane. However, the scenario with more dense traffic had a substantial workload as it required drivers to maintain a mental model of traffic, check the rear-view mirror, and steer around other cars when overtaking.

We ranked the conditions based on how well the drivers did on the driving task. Surprisingly, the results indicated that driving performance was not optimal in the condition without an additional task, regardless of the traffic circumstances. Instead, we found that the two radio tasks resulted in best driving performance, while the tablet task led to the worst. The ranking of tasks has several implications for multitasking during driving. The first, somewhat obvious, implication of this outcome is that visual interference affects driving more than aural or working-memory interference. The second implication is that some process separate from driving itself might affect driving when no secondary task is present. We argue that this process occurs in both driving scenarios. As both traffic situations are boring either through monotony or repetitiveness, drivers might engage in mind wandering. When someone starts mind wandering the attention is shifted from the drivers' surroundings towards task-irrelevant thoughts (Forster & Lavie, 2009; Giambra, 1995). Thus, people are creating their own distraction to alleviate boredom. Mind wandering can be seen as a type of self-induced visual interference: it causes the environment to no longer be monitored adequately (He, Becic, Lee, & McCarley, 2011), and driving performance suffers as a consequence. While this interference is not as strong as that which occurs with the tablet task, it does appear to impair driving ability more than the radio tasks. This means that the mildly interfering tasks we tested do not improve driving ability on a highway, they simply interfere less with driving than mind wandering does. That people mind wander during the study argues that they seek out multitasking. As the driving task itself is not very arousing in these circumstances, multitasking could be used as a strategy to increase arousal by increasing the number of cognitive resources that are used. Given how much time people spend mind wandering (Killingsworth & Gilbert, 2010), this is likely not a deliberate strategy, but perhaps a mechanism meant to keep one sufficiently aroused in order to stay awake.

Making Multitasking Decisions

In Chapter 4 we found evidence that drivers might not always make the best multitasking choices: sometimes they may choose to engage in mind wandering, which distracts from the main driving task. In Chapter 5 we explored this further by investigating whether the decisions people make about multitasking are rational. If they can choose what tasks to combine, do they try to maximize performance, or at least avoid the worst combination? Much like Chapter 2 and Chapter 3, we used a paradigm with three unique tasks to investigate this question. The main task was a subtraction problem that came in an easy and a hard variation. In the easy variation each column could be subtracted separately to calculate the answer, while in the hard variation people had to sometimes remember to carry between columns. The two secondary tasks were a counting task that used aural and working-memory resources, and a tracking task that used visual and motor resources. Based on the theory that resource overlap causes task interference due to the architectural constraints of the brain (Salvucci & Taatgen, 2008; Wickens, 2002), we can predict what task combinations work well together, and which do not. We predicted that combining an easy subtraction with the counting task would lead to the best performance, as there is no resource overlap between the tasks. We expected the lowest performance from a hard subtraction with the counting task, as overlap in working memory can have a substantial negative impact on performance (Borst, Taatgen, & Van Rijn, 2010; Jaeggi et al., 2003; Strayer, Cooper, & Turrill, 2013). Every thirty seconds participants were shown the difficulty of the next subtraction problem, and were able to choose what secondary task to perform. If people are able to evaluate how well they can multitask, and act rationally upon this, we would expect them to choose the counting task when subtraction is easy and the tracking task when subtraction is hard.

In a series of three experiments we showed that the performance result followed the a priori predictions that were based on the architectural limits of information processing. However, people appear to have a difficult time finding the task combinations that work best: around one in three did not adapt their secondary task choice to complement the subtraction difficulty. Of the remaining group, a small portion selected the secondary task seemingly at random, while the rest adapted to the combinations that had minimal overlap. Learning the optimal combinations was not a trivial undertaking: on average it took around half of the experiment, which corresponded to about 20 minutes, before task preferences stabilized. Thus, while (most) people have the capacity to make rational multitasking choices, there is a considerable learning curve. The fact that it takes time to understand what tasks combine well means that this is a strategic adaptation, and that the distributed architecture of multitasking itself does not help one intuitively understand what the limits of the multitasking mechanism are.

Concluding Remarks

The general perception towards multitasking has historically not been very positive. There is certainly sufficient evidence that supports the view that juggling several tasks at the same time should be avoided. Even in this thesis we found that people do not intuitively understand what activities can be performed well together. They may even choose to create an extra activity that does not complement the primary task, as we saw with mind wandering during driving. However, we have also shown that multitasking can improve driving ability in some circumstances, by providing a better alternative.

In this thesis we set out to determine what multitasking theory best explains the results of the driving experiment and the other paradigms. We considered three possibilities: performance suffers because there is a multitasking center that takes time away from task processes, due to structural limits of information processing in the brain that are exceeded during multitasking, or because the control strategies used for multitasking are not optimal. While we found no evidence for a multitasking center, untangling the remaining two options proved more difficult. In general, resource overlap between tasks was found to be an accurate predictor of multitasking interference. In other words, individual resources are used as serial bottlenecks whose availability is used to schedule how tasks are interleaved and executed. However, in order for working memory to behave as a serial bottleneck, we found that some additional task-dependent strategic control is required to manage the availability of working memory. Thus, the way in which the brain combines tasks concurrently is neither strictly architectural nor strictly strategic. Tasks are interleaved by a simple scheduling system that can be influenced by architectural and strategic factors. The studies in this thesis indicate that an architectural factor would be resource availability, while a strategic factor would be control over the availability of working memory.

Given the findings in this work, there is no simple answer whether or not you should choose to multitask. We can only supply a general guideline, which is that it is best to avoid combining activities that tax the same cognitive or peripheral systems. Such an understanding of the cognitive requirements of a task will likely reduce the learning curve observed when people try to understand what activities combine well. Beyond that, how well certain things can be done at the same time depends not only on the activities, but how experienced you are with them. Sufficient training can reduce the time required to perform a task, which makes it more likely that two tasks can be combined without interfering with each other. What is important to keep in mind is that there are many instances where multitasking does not come at a cost, yet allows us to perform several activities at the same time. In fact, it can even have positive effects as we saw with driving performance. Therefore, multitasking can be considered a very useful ability so long as it is used with some forethought.