Concurrent multitasking

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CHAPTER 1

Introduction

Where we discuss the relevant background literature and theories, followed by a brief overview of the contents of this dissertation.

Introduction

Introduction

In order to get anything done these days the conventional wisdom seems to be to turn off your phone, unplug the Internet connection, close the blinds, and hope nobody bothers you. In other words: avoid multitasking at all cost. And while I will be the last person to argue against 'monotasking', this does not change the fact that multitasking seems to have become a vital skill in our information-driven society. At least the number of cyclists who have their noses buried in their phones that I encounter during my daily commute seems to indicate so. But not only my own anecdotal evidence supports this claim; research has shown that we spend a lot of time performing several activities at once (Carrier, Cheever, Rosen, Benitez, & Chang, 2009). Given this prevalence of multitasking, it is important that we understand how and if our brain can juggle several tasks at the same time, when this is good idea, and when it is a bad one.

In this thesis I will investigate multitasking from the basic cognitive building blocks that allow us to perform activities concurrently, all the way up to the reasoning that people might use to determine when to multitask and which tasks to combine. I will use these different levels of description to better understand how the brain is able to multitask: is multitasking behavior controlled through a specialized area in the brain, is it a simple mechanism that relies on interactions between a distributed architecture of cognitive functions, or do we use specialized control strategies for every task combination we perform?

Throughout this work we will use overlap between tasks as a predictor of how well they can be performed concurrently. Tasks overlap when they require the same cognitive or peripheral resources at the same time. This leads to task interference, and thus has a negative impact on task performance. For example, cycling and reading text messages overlap because performing either task requires your visual system almost constantly. In fact, because the visual system is so crucial for both activities, any contention for it will likely lead to a dramatic reduction in cycling or texting ability, or both. Task interference can have different effects: in some cases it slows down task execution, as one task has to wait for another before using the same cognitive or peripheral function. Visual interference is an example of this. In other cases the interference might have more severe effects, such as information loss. This might be the case when there is task overlap for working memory. However, what task overlap also implies is that there are many tasks that can be combined without any issues: After all, simultaneously walking and talking is something we do all the time. Even a task as complex as driving, which requires you to monitor and control a host of things at the same time, is performed remarkably well by most people. Hence, the bad reputation that multitasking has garnered is not always deserved.

The goal of this work is to gain new insight into how the brain is able to perform more than one task at the same time. In pursuit of this goal I will present several experiments that test this idea through a combination of behavioral and neuroimaging methods. There will be a focus on interference in working memory, as our current description of interference in working memory is incomplete. I address this gap in knowledge by presenting a cognitive model of working memory interference.

To better understand the context of this work I will start with a brief overview of the relevant multitasking research: Task interference has long been studied, and the models presented in this work build upon that research. Furthermore, the models were constructed using ACT-R, so I will briefly describe this cognitive architecture. I will finish this introduction with an overview of the remaining chapters.

Background

Theories of Multitasking

For a long time researchers have been thinking about interference between concurrently performed tasks (e.g., Welford, 1952). During this early dual-tasking research the focus lay on temporal overlap between tasks, which was found to be a strong predictor of performance. This can be observed in a simple experiment with two choice-reaction tasks A and B. When both tasks must be performed concurrently, the reaction time (RT) for task B depends on the time between the presentation of stimuli A and B (see Figure 1-1). As the time interval becomes shorter, the RT for task B becomes longer. Thus, task A interferes with the performance of task B. The term Psychological Refractory Period (PRP; Telford, 1931) is used to describe this phenomenon. This PRP paradigm has been used in many areas of study, including aging (Allen, Ruthruff, Elicker, & Lien, 2009; Allen, Smith, Vires-Collins, & Sperry, 1998; Glass et al., 2000), attention (Brisson & Jolicoeur, 2007; Luck, 1998), and perceptual interference (Van Maanen, Van Rijn, & Borst, 2009).

The PRP effect has been explained by a response selection bottleneck (RSB; Pashler, 1994). The RSB model distinguishes three phases in the component tasks of the PRP dual-task: perception, response selection, and response. The RSB assumes that perception and response can occur in parallel during a dual task, but response selection can only be performed sequentially (Pashler, 1994). The RSB predicts that as the stimulus onset asynchrony (SOA) becomes smaller, the response selection phase of task A will increasingly delay that of task B: both responses cannot be resolved in parallel. This delay then leads to a larger reaction time for task B (Figure 1-1). This concept of a bottleneck as the cause of task interference has become a staple of modern multitasking theories (Just & Varma, 2007; Meyer & Kieras, 1997; Salvucci & Taatgen, 2008; Wickens, 2002).

Most modern multitasking theories contain elements of the RSB. The multiple resource theory (Wickens, 2002), for instance, defines a great number of bottlenecks that include both cognitive and response-related stages in task processing, as well as sensory modalities and multiple information channels. Given the number of overlapping resources, multiple resource theory can be used to predict the expected performance decrease when multitasking. The bottleneck principle has also been

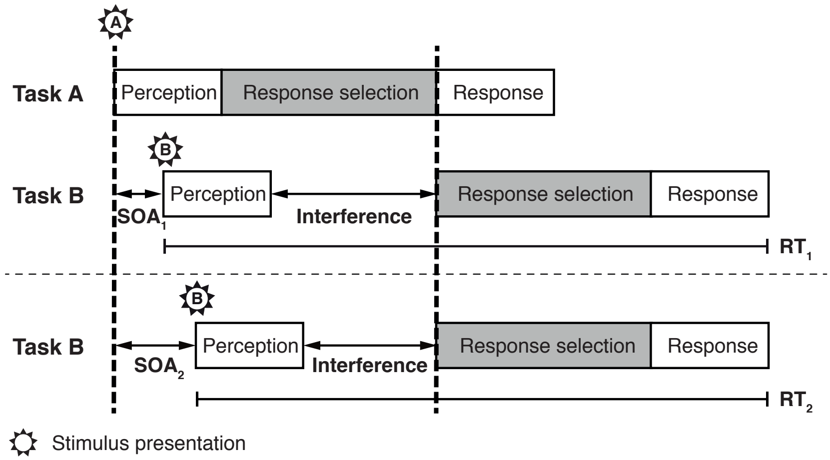

Figure 1-1. The PRP effect. A shorter onset delay for the task B stimulus (shown in the bottom row) can result in a longer RT as the Interference period will last longer in that condition.

applied in more general cognitive theories. An example of this is EPIC (Executive-Process Interactive Control; Meyer & Kieras, 1997), where central cognitive resources, such as declarative memory, can be accessed in parallel, but peripheral resources, such as vision, act as a bottleneck. The EPIC theory promotes the view that multitasking occurs as a control strategy that describes how to perform a specific task combination. These strategies might have overhead costs or prioritize a task, leading to reduced performance when multitasking. Another theory that uses the RSB theory in a more general manner is ACT-R (Anderson, 2007): all resources, both peripheral and cognitive, are constrained to serial access (Byrne & Anderson, 2001). However, by default ACT-R is limited to performing a single task at any given time. Salvucci & Taatgen (2008) developed an extension for multitasking to ACT-R called threaded cognition, which allows for the execution of multiple tasks in parallel (while resources are still constrained to serial access). This approach to multitasking behavior is architectural: how processes of separate tasks are scheduled depends largely on the availability of resources that are distributed throughout the brain. This infers that the brain has a limited bandwidth for information processing, and task performance is reduced when this limit is exceeded.

Multitasking Behavior

Multitasking theories have been used to explain many different examples of multitasking behavior. Perhaps the most prolific example is multitasking during driving. This particular multitasking situation has received a great deal of attention due to the high number of traffic-accidents that have been attributed to phone use during driving (Redelmeier & Tibshirani, 1997). Strayer and Johnston (2001) showed that it is the attentional component of holding a conversation that affects driving performance most. They reached this conclusion by ruling out explanations related to holding the phone, speaking, or listening. Using a phone is hardly the only task that has been shown to interfere with driving: in general, any concurrently performed task that has a perceptual (visual and auditory; Chaparro, Wood, & Carberry, 2005; Gherri & Eimer, 2011) or motor (manipulation of equipment; Briem & Hedman, 1995; Brookhuis, de Vries, & de Waard, 1991) component can compromise driving performance. The general picture of tasks that interfere with driving is consistent with current theories of multitasking: interference occurs because driving requires the same resources that the examined secondary tasks use (Anstey, Wood, Lord, & Walker, 2005; Herbert, 1963).

Perhaps less intuitive is that interference between driving and other activities extends to overlap in working-memory requirements: Alm and Nilsson (1995) performed a study where drivers had to complete a word-recall task over the phone while driving. They found that this affected driving safety, as it decreased the distance kept to the car ahead of the driver. Working memory interference has been investigated in other contexts as well (Gray, Sims, Fu, & Schoelles, 2006; Jaeggi et al., 2003). For example, Borst, Taatgen, and Van Rijn (2010) showed that when switching between two tasks, performance suffered most when both tasks required working memory. The reason this occurs is that the current state of the suspended task needs to be kept in working memory in order to properly resume that task later. When the state of the other task also needs to be kept in working memory, interference occurs when the old (suspended) state is swapped out for the new state and vice versa. This work by Borst et al. has improved our understanding of how working-memory interference occurs when tasks are alternated, something that is also referred to as sequential multitasking. However, our understanding of working-memory use during concurrent multitasking is limited: theories that address concurrent multitasking do not describe working memory in detail (Just & Varma, 2007; Meyer & Kieras, 1997; Salvucci & Taatgen, 2008; Wickens, 2002).

In addition to being studied at the cognitive level, multitasking has been examined in its influence on society as well. People have been found to multitask frequently at the workplace (Mark & Gonzalez, 2005) or in the classroom (Junco & Cotten, 2011). As these places suggest a significant integration of multitasking with our daily lives, it is important to understand why people choose to multitask. Factors that have been found to play a role in choosing to multitask are personality traits such as impulsivity or sensation seeking, as well as the inability to block out distractions (Sanbonmatsu, Strayer, Medeiros-Ward, & Watson, 2013). However, while these factors address why people multitask, there is currently not much research regarding how people decide what activities to combine when choosing to multitask.

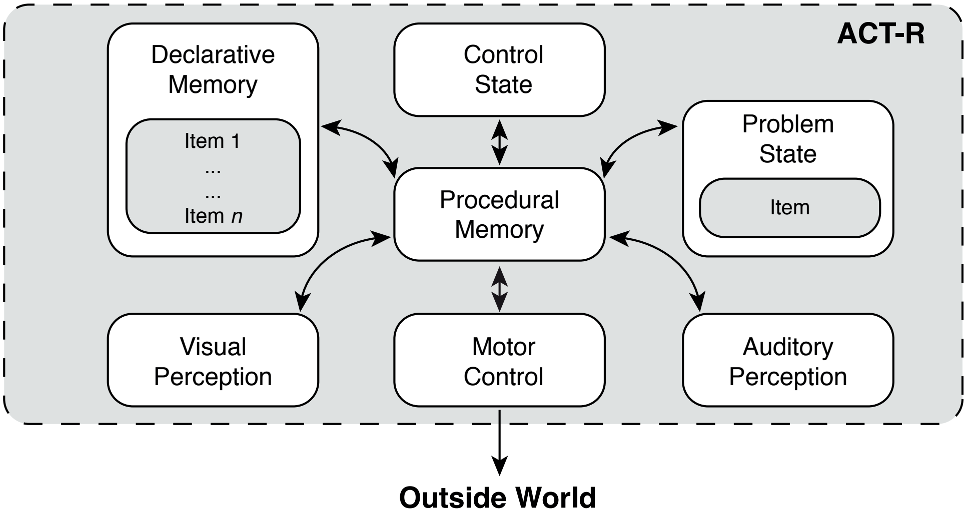

Figure 1-2. The module structure of the ACT-R cognitive architecture.

Cognitive Modeling

Both the EPIC and ACT-R theories described earlier have been instantiated as cognitive architectures. A cognitive architecture provides a framework in which processes that occur in the brain can be modeled. The models described in this thesis are such computational models of cognition. Models of this kind are able to perform tasks by simulating the required cognitive processes. Behavioral output of the model (i.e., the model presses a button) can then be compared to the behavior shown by real humans in order to determine if the model is a plausible one. In general, the detail and scope of cognitive models can vary greatly: from a mathematical model consisting of a single formula to the large cognitive architectures of EPIC and ACT-R. For this thesis ACT-R is of particular importance, as all the models that I will present have been built upon it.

ACT-R

ACT-R contains modules for cognitive and peripheral functions, shown in Figure 1-2. While these modules can only be accessed serially, different modules can be used in parallel (Byrne & Anderson, 2001). Procedural memory is used to coordinate actions between these modules, using a set of if-then rules. A rule can, for instance, be '*if* the visual module contains a letter, *then* store this letter in memory'.

Two ACT-R modules are of particular relevance to this thesis, because they can be used as part of a working memory strategy: declarative (long-term) memory and the problem state. Declarative memory is a storage place for facts. Although the capacity of declarative memory is essentially unlimited, the chance of being able to retrieve an item decreases over time. Furthermore, retrieval of information from declarative memory takes time, and existing information is immutable. The problem state is a buffer that can contain a single piece of intermediate information used by a task (Borst et al., 2010). For instance, when presented with a 'solve-for-x' equation with two steps, an intermediate solution can be stored in the problem state. This partial solution can then be used to calculate the final answer. While information in the problem state is accessed without a time cost, replacing it takes a relatively long time. When a problem state is replaced, the old state is stored as an item in declarative memory.

To have two tasks performed concurrently in ACT-R requires threaded cognition (Salvucci & Taatgen, 2008). It adds a parsimonious scheduling system to ACT-R that interleaves the execution of task rules: the next rule to be picked will belong to the task with the highest urgency. The task with the highest urgency is the one that has least recently had a rule picked. If no rule of that task can be executed at this time, then the next most-urgent task is selected. For this system to work, the tasks are expected to be polite: they must release access to a module as soon as the task no longer requires it. Otherwise a task could occupy a module indefinitely, and the other tasks would (potentially) never finish.

Dissertation Overview

This dissertation will focus on how overlapping task requirements affects the way our brain processes multitasking situations, and how it influences the behavior of people when multitasking. We aim to answer the following questions: Is there a multitasking center in the brain, or are tasks coordinated using more general cognitive mechanisms? Do people make rational choices when multitasking, and does this happen automatically? And is multitasking always bad for performance when driving a car, or can it be beneficial?

In Chapter 2 I will present a neuroimaging experiment that explores how multitasking activity is expressed in the brain. Chapter 3 extends this investigation into the mechanisms of multitasking through a cognitive model that details how task interference in working memory can be explained. This model is validated using the neuroimaging data from Chapter 2 as well as novel behavioral data. In Chapter 4 the focus will shift from cognitive processes to human behavior. I will describe a study that tests the effect of different degrees of task interference with driving on driving performance in two different types of traffic circumstances. Next in Chapter 5 I test whether or not people try to minimize task overlap when choosing tasks to perform concurrently. Finally, Chapter 6 gives an overview of the results presented in this thesis, and how they inform us about the cognitive mechanisms that make multitasking possible.