TASK SWITCHING AND COGNITIVE CONTROL

EDITED BY
JAMES A. GRANGE &
GEORGE HOUGHTON

OXFORD

TASK SWITCHING AND COGNITIVE CONTROL

TASK SWITCHING AND COGNITIVE CONTROL

EDITED BY JAMES A. GRANGE

AND

GEORGE HOUGHTON

OXFORD
UNIVERSITY PRESS

Oxford University Press is a department of the University of Oxford.
It furthers the University's objective of excellence in research, scholarship,
and education by publishing worldwide.

Oxford New York
Auckland Cape Town Dar es Salaam Hong Kong Karachi
Kuala Lumpur Madrid Melbourne Mexico City Nairobi
New Delhi Shanghai Taipei Toronto

With offices in
Argentina Austria Brazil Chile Czech Republic France Greece
Guatemala Hungary Italy Japan Poland Portugal Singapore
South Korea Switzerland Thailand Turkey Ukraine Vietnam

Published in the United States of America by
Oxford University Press
198 Madison Avenue, New York, NY 10016

[Insert Cataloguing Data]

ISBN 978–0–19–992195–9

9 8 7 6 5 4 3 2 1

Printed in the United States of America
on acid-free paper

CONTENTS

CONTRIBUTING AUTHORS

Erik M. Altmann
Michigan State University, USA

Catherine M. Arrington
Lehigh University, USA

Eveline A. Crone
Leiden University, the Netherlands; Leiden Institute for Brain and Cognition, the Netherlands; and University of Amsterdam, the Netherlands

Abhijit Das
Kessler Research Foundation, USA; Rutgers University, USA

Michel D. Druey
University of Zurich, Switzerland

Miriam Gade
University of Zurich, Switzerland

Nicola K. Ferdinand
Saarland University, Germany

James A. Grange
Keele University, UK

George Houghton
Bangor University, UK

Sharna D. Jamadar
Monash University, Australia

Frini Karayanidis
University of Newcastle, Australia

Alexander Kirkham
University of York, UK

Iring Koch
RWTH Aachen University, Germany

Jutta Kray
Saarland University, Germany

Gordon D. Logan
Vanderbilt University, USA

Paloma Marí-Beffa
Bangor University, UK

Nachshon Meiran
Ben-Gurion University of the Negev, Beer-Sheva, Israel

Sabine Peters
Leiden University, the Netherlands; Leiden Institute for Brain and Cognition, the Netherlands

Susan M. Ravizza
Michigan State University, USA

Kaitlin M. Reiman
Lehigh University, USA

Franziska R. Richter
University of Oxford, UK

Ruth E. Salo
University of California Davis, USA

Darryl W. Schneider
Purdue University, USA

Stefanie Schuch
RWTH Aachen University, Germany

Starla M. Weaver
Kessler Foundation Research Center, USA

Glenn R. Wylie
Kessler Research Foundation, USA; University of Medicine and Dentistry of New Jersey, USA

Nick Yeung
University of Oxford, UK

1

Task Switching and Cognitive Control

An Introduction

JAMES A. GRANGE AND GEORGE HOUGHTON ■

INTRODUCTION

Humans live in an increasingly busy, multitask environment, requiring frequent switching between different cognitive operations and tasks. Driving, for example, presents us with an incredibly complex environment in which many subtasks—e.g., speed monitoring, interpretation of abstract road signs, planning the best route, etc.—must be organized and deployed appropriately to arrive at our destination safely. Even simple acts require effective scheduling and deployment of cognitive operations: For example, making a cup of coffee requires memory retrieval (Where did I store the coffee?), planning (fill the kettle with water *before* turning it on), mental rotation (read the coffee labels to avoid selecting the "de-caf"), coordination of both hands to open the coffee jar, and so on. Yet, despite the hustle and bustle, humans are able to act in a goal-directed manner. The question thus arises as to how humans are able to organize and control the selection and deployment of ongoing cognitive processes to ensure successful performance in multitask environments.

This problem is confounded because stimuli in our environment typically afford more than one action, making stimulus-dependent responding impossible; many of these competing actions are often totally irrelevant for the current task. For example, sat at a computer with the intention to write a book manuscript—how do we select this task in the face of competing tasks such as checking our email, browsing an online bookstore, or playing *just one more* game of online chess before we begin our work?

The cognitive system must be able to select the appropriate task based on current goals and intentions, rather than relying on stimulus-evoked actions. Such selection sometimes fails, as we have all likely experienced in the form of "action slips" (Reason, 1984)—putting a tea bag in your mug instead of coffee is one common example. Pathologically, damage to the prefrontal cortex has been shown to be sometimes associated with "utilization behaviour" (Lhermitte, 1983), where patients are not able to resist goal-irrelevant actions afforded by stimuli presented to them; walking past a light switch, a patient with utilization behavior might not be able to resist the urge to switch it on, even if lights are not required.

Thus, some form of top-down control is required to *select* the goal-relevant task in the face of competing alternatives. This *cognitive control* is imperative to ensure behavior is not stimulus driven. However, selection of relevant tasks is only one problem that the cognitive system must solve. Once a relevant task *has* been selected, how is this task able to dominate behavior so that competing tasks are not able to intrude? There would be little use for a system that can select relevant tasks with ease but is unable to maintain this task once competitors are present (otherwise, book manuscripts would never be finished). Therefore, the system needs to ensure the *stability* of task-relevant representations once a task has been selected. Somewhat paradoxically, although task representations must be stable, they must also be *flexible*, so that the representation can be removed and replaced when goals change. Failure to remove and update relevant task representations would lead to perseveration of action. The tension between these opposing demands has been called the *stability–flexibility dilemma* (Goschke, 2000), and it is a challenge for researchers of cognitive control to understand the mechanisms that allow the balance to occur. A system that solves the stability–flexibility dilemma would be well placed to adapt to changing situations and to act in a goal-directed manner.

THE TASK SWITCHING PARADIGM

The present volume is dedicated to a discussion of one set of tools that researchers of cognitive control have used to try to understand the mechanisms that allow a resolution to the plethora of demands placed on the cognitive system in multitask environments. The *task switching paradigm* has garnered much research interest over the past 20 years, driven by the potential that it allows measurement of cognitive control processes in operation (Kiesel et al., 2010; Meiran, 2010; Monsell, 2003; Vandierendonck, Liefooghe, & Verbruggen, 2010). In task switching paradigms, participants are typically presented with stimuli that afford more than one action (e.g., numbers) and are required to perform one of two tasks on the stimuli (e.g., odd/even judgments and lower-than-5/higher-than-5 judgments). Successful performance in such situations requires careful selection and maintenance of the currently relevant task and the flexibility to update tasks when goals change. It is a well-replicated finding in such task switching experiments that switching tasks induces a performance cost—typically manifesting in slower response times (RTs) and increased errors—compared with repeating tasks. Many researchers (though far from all) have taken this so-called *switch cost* as reflecting the time-course of a—or a set of—cognitive control processes dedicated to task switching (Meiran, 1996; Meiran, Chorez, & Sapir, 2000; Rogers & Monsell, 1995;

cf. Altmann & Gray, 2008, Allport, Styles, & Hsieh, 1994, Logan, 2003), and—by inference—that this cost is an important phenomenon with which to explore cognitive control. Thus, the growth in task switching research reflects interest in the possibility that understanding the nature of the switch cost will allow us to understand the cognitive processes that solve the stability–flexibility dilemma and to understand how efficient goal-directed behavior is produced.

The boom of interest in task switching research is highlighted by examining citation records of key task switching articles. For example, a key publication that reinvigorated research into task switching (Rogers & Monsell, 1995) has been cited 1,213 times[1]; a review in 2003 from the same group (Monsell, 2003) has been cited 774 times. Lest readers think interest in task switching is fading, two updated reviews of task switching—both published as recently as 2010—(Kiesel et al., 2010; Vandierendonck et al., 2010) have already accrued impressive citation counts in such a short time (124 and 77 citations, respectively). It is thus timely that a volume be dedicated to the research conducted on task switching.

CHAPTER OVERVIEW

The purpose of the present chapter is to provide the reader with a broad overview of task switching in general and to provide an overview of some of the different task switching paradigms available to the researcher, together with brief discussion of key empirical phenomena that are measured in these paradigms and how each is thought to be related to key cognitive control processes. Although some of these paradigms and empirical phenomena are the subject of dedicated chapters in this book—specifically, Chapters 3 (Meiran), 4 (Marí-Beffa & Kirkham), 5 (Altmann), and 6 (Arrington, Reiman, & Weaver)—we provide brief overviews here to give the reader sufficient background knowledge to tackle this book in any order. The overview is designed to be rather superficial, mainly highlighting the main trends in task switching research, making it as accessible as possible to new researchers to task switching. As we have noted, two excellent and comprehensive systematic reviews of task switching were recently published (Kiesel et al., 2010; Vandierendonck et al., 2010) that provide in-depth coverage of everything discussed in this chapter; however, we still aim to give a reasonably broad overview of the field here to ensure the book can stand alone.

After reviewing the paradigms and main empirical phenomena of task switching research, we provide an overview of the chapters in the present volume. We have been fortunate that each chapter is written by groups of leading authorities in their respective specialties; thus, this volume provides the reader with state-of-the-art knowledge of task switching research. Not only does each chapter provide comprehensive reviews, but they also are full with ideas for future directions in task switching research. Thus, these chapters will also provide the reader with many avenues with which to explore in their own research program.

Broadly, the book can be considered to be presented in three sections. The first "section" (Chapters 2 to 8) addresses key task switching paradigms and phenomena/concepts in more detail than the current chapter; these paradigms and effects reflect important areas of task switching research, and as such warrant their own chapters. This section also provides an overview of computational/mathematical models of task switching, which reviews the efforts of researchers to model and integrate key task switching effects. The second section (Chapters 9 and 10) deals with the neuroscience of task switching, focusing on the temporal (Chapter 9) and spatial (Chapter 10) localization of cognitive control processes during task switching. These chapters provide comprehensive reviews of the neural correlate of task switching performance in healthy populations. Section 3 addresses research on task switching and cognitive control in atypical research populations, including those with executive dysfunction (Chapter 11) and psychiatric disorders (Chapter 12). This section also includes comprehensive reviews of the developmental trajectory of task switching and cognitive control throughout the life span, covering research of task switching in childhood/adolescent populations (Chapter 13) and older adults (Chapter 14). It is hoped that the broad scope of topics covered in this book will appeal to readers from a wide range of research disciplines, including cognitive psychology, cognitive neuroscience, cognitive neuropsychology, clinical psychology, developmental psychology, human factors, and cognitive science.

TASK SWITCHING AND COGNITIVE CONTROL: PARADIGMS AND EMPIRICAL PHENOMENA

This section provides a chronological overview of trends in task switching research to date. Along the way, we highlight key experimental paradigms that have been used to measure cognitive control during task switching. Empirical phenomena in such paradigms have led researchers to hypothesize as to the nature of the control processes operating, although some of these processes are still hotly debated today.

Early Work and the Concept of Task Sets

The work of Jersild (1927) is typically cited as among the first empirical investigations into task switching (although Meiran, 2010, mentions earlier work by Ach, 1910). He presented participants with lists of stimuli (e.g., numbers) and required participants either to work through the list using just one task for all stimuli (repetition list, hereafter referred to as "pure" blocks or "pure" lists; e.g., add 3 to each number) or to alternate between two tasks (alternation list; e.g., add 3 to the first number, subtract 6 from the second, and repeat this pattern until the list is complete). Jersild's results showed that list-completion time was slower when participants were required to switch between two tasks than when just one task was required (see also Spector & Biederman, 1976), an effect the reader can replicate in Figure 1.1.

8—11—6—16—15—19—12—17—9

Figure 1.1 An example of the list paradigm (Jersild, 1927). Time yourself in two conditions. In the first condition, work through the list of numbers, adding 3 to each number (task repetition or "pure" list). In the second condition, work through the list of numbers, adding 3 to the first number, subtracting 6 from the second number, and repeating this pattern until you reach the end of the list (alternation list). Your list-completion times should be slower for the alternating list than for the repetition list.

Jersild (1927) suggested that to perform successfully on this paradigm, participants must establish in their mind a set of task rules and representations that allow correct performance. For example, when performing the addition task, the participant must activate in working memory some form of representation of "addition" that allowed successful execution of this task. Establishing new mental sets takes time, as reflected in the slower list-completion times for alternation lists compared with pure lists: Alternation lists require updating of mental set on every stimulus, whereas pure lists require maintaining the same mental set throughout. To Jersild, then, the list-alternation cost reflected the time taken to update one's mental set.

The concept of mental set has been expanded in recent years and is now typically referred to as a *task set*. Although the operational definition of task set varies with researcher (or goes undefined/underspecified; see Logan & Gordon, 2001; Schneider & Logan, 2007a; Schneider & Logan, Chapter 2, this volume), there are some definitions to be found in the task switching literature. Rogers and Monsell (1995), for example, define a *task set* as "form[ing] an effective intention to perform a particular task" (p. 207). Logan and Gordon (2001)—in their model of executive control of visual attention in dual task situations (ECTVA)—suggest that a task set consists of a set of programmable parameters critical for successful task performance that affect task processes, such as response selection, attentional bias, etc.; when the task changes, these parameters must be updated. Mayr and Keele (2000) offer a similar definition, stating a task set is "the configuration of perceptual, attentional, mnemonic, and motor processes critical for a particular task goal" (p. 5). Meiran (2010) has more recently suggested that a task set consists of five main elements[2]: (a) a goal state, (b) selection of task-relevant information through attention, (c) activation of task-relevant semantic information (e.g., in the case of the example in Figure 1.1, performance of an addition task requires activation of relevant numerical information [addition rules, etc.]), (d) activation of response information affording readiness to respond (e.g., in modern studies, participants might have to learn to associate a left key press with either an odd or a lower-than-5 response; depending on the currently relevant task; so-called *stimulus–response rules*), and (e) activation of correct response rules for presented stimulus (e.g., stimulus is odd, so press left).

Despite these somewhat inhomogeneous definitions, they all share the implicit assumption that task sets must be updated when the relevant task changes.

Establishment of a robust task set has been shown to shield the cognitive system effectively from distracting elements in multitask situations (Dreisbach, 2012; Dreisbach & Haider, 2008, 2009). For example, if a participant has firmly established the task set of "color naming," then they should be less prone to interference during a Stroop task (Stroop, 1953) when presented with the word "GREEN" written in red ink (and, with relevance to the example provided earlier, establishing the task set of "writing book chapter" should reduce interference from email distractions). Thus, establishing a suitable task set seems one way to ensure stability of task performance.

Alternating Runs Paradigm and Task Set Reconfiguration

At first, it seems the list paradigm is a suitable tool to measure the cognitive control processes required to update task sets when a change in task occurs: It produces a robust cost to performance, which is thought to index the time required to update task sets in working memory. However, despite it still being used sporadically (e.g., Baddeley, Chincotta, & Adlam, 2001; Bryck & Mayr, 2005; Emerson & Miyake, 2003), fundamental shortcomings with its construct validity render the list paradigm largely absent from modern task switching research. There exist other demands on the cognitive system than the requirement to switch task sets in the alternating lists compared to pure lists. One important factor is the differential load on working memory in the two list conditions: Pure lists require the maintenance of just one task set in memory, whereas alternating lists require participants to keep two task sets in a state of preparedness (Los, 1996; Philipp, Kalinich, Koch, & Schobotz, 2008; Poljac, Koch, & Bekkering, 2009; Rubin & Merian, 2005).

Indeed, later research demonstrated that task repetition RTs in pure lists (e.g., A*AAA*. . .) are faster than task repetitions in mixed lists (e.g., A*A*B*B*. . . ; see later for more elaboration on mixed lists), even though both are strictly task repetitions. This *mixing cost* has been rather neglected in task switching research (but see seminal studies by Los, 1996; Rubin & Meiran, 2005; and more recent investigations: Marí-Beffa, Cooper, & Houghton, 2012) but could reflect important cognitive control processes. For example, Mari-Beffa and Kirkham (Chapter 4, this volume) argue that the mixing cost is an important measure of sustained mental control processes in multitask situations. Regardless of the true cause of the mixing cost, its presence complicates the issue when comparing pure and alternating lists in the Jersild (1927) paradigm as the costs to performance might not reflect the time-course of task set updating—and are thus potentially not an important signature of cognitive control, because the cost might reflect the extra demands on working memory during alternating lists.

To overcome this problem, Rogers and Monsell (1995)—in a seminal report that reinvigorated interest in task switching—introduced the *alternating runs paradigm*; this allowed investigation of responses to task repetition and task switching trials while equating working memory load (cf. Jersild, 1927). The alternating runs paradigm required participants to switch between two simple tasks every

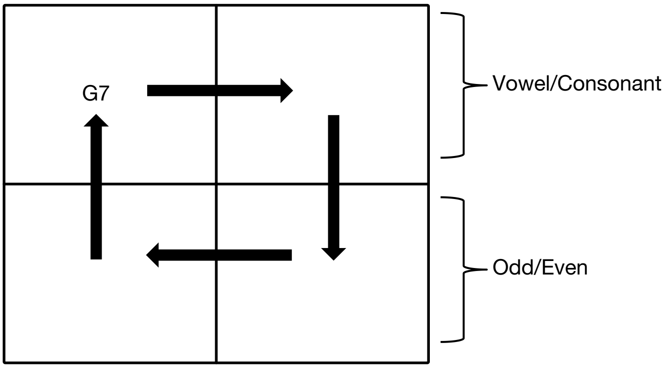

Figure 1.2 Example of the alternating runs paradigm (Rogers & Monsell, 1995). The stimulus location rotated in a predictable clockwise fashion on every trial, with the task switching when the stimulus crossed the horizontal mid-section. Performance in the upper-left and the lower-right squares thus reflects task switch trials, whereas performance on the upper-right and the lower-left squares reflects task repetition trials.

second trial in a predictable manner (e.g., AABBAABB. . ., etc.). Memory load was reduced in this experiment by presenting participants with a 2 × 2 grid with the location of the imperative stimulus rotating clockwise every trial (see Figure 1.2). If the stimulus appeared in either of the two upper squares, participants had to perform one task (e.g., vowel/consonant judgment on the letter), and when the stimulus appeared in the lower squares, participants had to perform the other task (e.g., odd/even judgment on the number stimulus; see Figure 1.2): Task switches occurred when the imperative stimulus moved across the horizontal mid-section, and other trials are task repetitions (e.g., moving from top-left to top-right requires repeating the vowel/consonant task). Thus, task switches and task repetitions occur in the same block of trials and memory load is equated (cf. Jersild, 1927).

As stimuli were mostly bivalent (in that the stimulus equally afforded both tasks), task performance required establishing a relevant task set. Thus, the finding of increased RTs and error rates to task switches compared to task repetitions led Rogers and Monsell (1995) to posit that this switch cost reflected the time taken for the cognitive system to reconfigure the relevant task set in memory; that is, the task set parameters relevant to the previous trial need to be removed and replaced with parameters relevant for the current trial. This time-consuming *task set reconfiguration* is required only on switch trials, as the previously applied task set is no longer relevant; repetition trials do not require any reconfiguration as the previous task set is applicable to the current trial. Using subtraction logic of RT analysis (e.g., Sternberg, 1969)—that responses to switch trials required only the addition of a task set reconfiguration stage, in comparison to task repetition trials, which do not—Rogers and Monsell hypothesized that the switch cost reflects the temporal signature of cognitive control in operation (although, as we will see, this has not met with consensus in the literature).

In apparent confirmation of the reconfiguration hypothesis, Rogers and Monesll (1995) found that the switch cost was significantly reduced if participants were given sufficient preparation time prior to target onset; this is consistent with a reconfiguration account as preparation time allows the time-consuming reconfiguration process to occur prior to target presentation (for an excellent overview of task preparation and its associated empirical evidence, see Kiesel et al., 2010).

Preparation time in the alternating runs paradigm is manipulated by varying the *response–stimulus interval (RSI)*: the time between the response to one task and the onset of the stimulus for the next task. The authors varied the RSI between 150 milliseconds (ms) and 1,200 ms and found that switch cost was indeed reduced at longer RSIs. This *reduction in switch cost (RISC)* has been taken as strong evidence for a reconfiguration process (Monsell, 2003; but see Logan & Bundesen, 2003, and the rejoinder Monsell & Mizon, 2006). However, even at prolonged RSIs, a small but consistent switch cost remained; this *residual switch cost* was subject to a flurry of investigation in subsequent years, with two main hypotheses for its presence: that it reflected a fundamental limit of reconfiguration based on sufficient task preparation (e.g., De Jong, 2000) and that there was an influence of the task stimulus on performance (Mayr & Kliegl, 2003; Rogers & Monsell, 1995; Rubinstein et al., 2001).

Rogers and Monsell (1995) supported the latter, suggesting that task set reconfiguration consisted of an endogenously driven reconfiguration process and a second, exogenous, component that must wait for stimulus presentation to commence. This two-stage account is in line with Mayr and Kliegl (2000, 2003), who suggested that task switching requires retrieval of task rules—a "relatively abstract description of what has to be done with the next stimulus" (Jost, Mayr, & Rösler, 2008, p. 75)—from long-term memory (together with their installation into working memory) and the application of these rules to the stimulus (e.g., if the stimulus is odd, press the left response key, and if the stimulus is even, press the right response key). The former process can be achieved ahead of target presentation (accounting for the large RISC with increased preparation time), but the latter process must wait for target presentation to be completed (thus accounting for the residual switch cost, but see Jost et al., 2008, and Monsell & Mizon, 2006, for evidence that this process can begin earlier than target onset).

Other authors suggested the residual switch cost reflected a fundamental limit of task preparation. Rather than reflecting a two-stage process that must wait for target onset to be completed, these theories suggest that full reconfiguration is possible before target onset but that it does not occur for a variety of reasons. The most influential theory in this respect is De Jong's (2000) *failure to engage* (FTE), which posits that full advanced reconfiguration is possible but participants do not engage this preparation on all trials. FTE suggests that preparation is an all-or-none process (cf. Lien et al., 2005) and that performance during task switching therefore consists of a mixture of fully prepared and unprepared trials. This transient nature of preparation was suggested to be driven by one of three (or any combination thereof) factors: (a) absence of goal-driven intention (i.e., motivation is lacking), (b) low environmental support (e.g., in the alternating runs paradigm, requiring to hold a task sequence in memory rather than being cued by stimulus position on screen), and (c) fatigue.

Task-Set Inertia

The hypotheses of the switch cost discussed so far assume it reflects an endogenously driven cognitive control process, namely task set reconfiguration. However, around the same time as Rogers and Monsell's (1995) investigation, Allport and colleagues (Allport, Styles, & Hsieh, 1994; Allport & Wylie, 2000) were also beginning to investigate task switching, developing their *task set inertia* (TSI) hypothesis. TSI explains switch cost not as a time-consuming reconfiguration process but rather as arising from familiar memory processes such as priming and interference (see also Altmann, 2002, 2003a, 2003b, Altmann & Gray, 2002, 2008). From this perspective, the switch cost can—on a task switch trial—be explained by persisting activation of the previous, but now irrelevant, task from the previous trial; this persisting activation—together with negative priming of the relevant task (see later)—hinders implementation of the currently relevant task, creating interference. The switch cost from the TSI perspective thus reflects the time taken to resolve this interference and establish the desired task set. Note also that this account provides an elegant explanation of the residual switch cost: that it is caused by proactive interference from elements of the previous task, independent of any preparation time (see Vandierendonck et al., 2010, for elaboration). Although the TSI account does not deny the requirement of cognitive control during task switching (Logan, 2003), it *does* deny that the switch cost directly measures the time-course of cognitive control operations. The cognitive system faces the same challenge on task switch trials that it also faces on task repetition trials: that of ensuring the relevant task is the most active among all competitors (see also Altmann & Gray, 2008).

Support for this hypothesis comes from the so-called *asymmetric switch cost*: The observation that—when switching between tasks of unequal difficulty—the switch cost is greater when switching from the difficult to the easy task compared with switching from the easy task to the difficult task. Allport and colleagues suggested this cost arises as performance of the difficult task when switching from the easy task is hindered by the dominant activation of the easy task, causing interference; this interference needs to be resolved, by activating the difficult task (which takes time due to its difficulty) and negatively priming (i.e., inhibiting) the easy task. When switching back from the difficult task to the easy task, the activation of the difficult task persists, as does the inhibition of the easy task. Together, the inhibition of the relevant task (negative priming) and the increased interference from the irrelevant task (positive priming) cause uncertainty in the system, which takes time to resolve; the net effect is a large switch cost. Conversely, when switching from a difficult to an easy task, because the easy task is so dominant, there will be less necessity to strongly activate it (leading to reduced positive priming on the next trial) and the difficult task would require less/no inhibition (leading to reduced negative priming on the next trial). This effect replicates well (Arbuthnott, 2008a; Meuter & Allport, 1999; Monsell, Yeung, & Azuma, 2000; Yeung & Monsell, 2003; but see Schneider & Anderson, 2010, for an alternative interpretation of this cost). These data present a strong challenge to the reconfiguration hypothesis (see Gilbert & Shallice, 2000), which would predict a greater switch cost in switching from the easy task to the difficult task (as more needs to be "reconfigured"); the reconfiguration account also predicts no "carry-over" of previous (i.e., irrelevant) task activation once reconfiguration has occurred, contrary to what is observed.

The TSI account explains reduction of switch cost at extended preparation intervals (the RISC) by the dissipation of activation of irrelevant tasks (plus the dissipation of inhibition of the relevant task). During switch trials at short RSIs, the previous task's representation will still be very active, generating proactive interference. At extended RSIs, the previous task's activation will have decayed, eliciting less proactive interference. Thus, according to this view, observation of reduced switch cost with extended preparation time does not suggest a reconfiguration mechanism is in operation.

Both the TSI and reconfiguration hypotheses mimic each other in predicting a reduction of switch cost at extended RSIs. The reconfiguration account states this reduction is due to preparation-based reconfiguration of task sets (and thus the switch cost reflects cognitive control), whereas the TSI account predicts the reduction due to reduced proactive interference (and thus the switch cost does not reflect cognitive control). As extending the RSI in the alternating runs paradigm increases time for preparation *and* time for the previous tasks' activation to decay, it was clear that this paradigm was not suited to differentiate the competing hypotheses; as such, the alternating runs paradigm is seldom used in modern task switching research (see Altmann, 2007, for further important shortcomings of the alternating runs paradigm).

Explicit Cuing Paradigm

Meiran (1996; see also Chapter 3, this volume) and Meiran, Chorev, and Sapir (2000) used the *explicit cuing paradigm* (see also Sudevan & Taylor, 1987) to differentiate between the reconfiguration and TSI account of the switch cost. In this paradigm, participants must switch between two (or more) tasks on multivalent stimuli. Task presentation is random (cf. the fixed structure of the alternating runs), and participants know which task is currently relevant by a valid task cue that instructs them as to which task to perform. Trials are categorized into switch or repeat trials by comparing the cue on the previous trial with that of the current trial. Meiran's task presented participants with a 2×2 grid, with a target appearing in one of the four quadrants of the screen. The tasks were to either judge whether the stimulus appeared in the upper or lower two quadrants (up/down judgment) or in the left or right two quadrants (right/left judgment). The cues presented were two arrows, either pointing up and down (to cue the up/down task) or pointing left and right (to cue the left/right task).

This elegant paradigm allows researchers to separate the contributions of preparation-based processes (e.g., advanced reconfiguration) and TSI on the switch cost. Instead of manipulating the RSI, researchers now have control over two experimental parameters: The *cue–stimulus interval (CSI)* and the *response–cue interval (RCI)*. The CSI is the time between the onset of the task cue and the appearance of the trial target; extension of this period affords more time for task-specific preparation. The RCI is the time between the response to the previous task and the onset of the cue for the next task; extension of this period affords more time for the previous task's activation levels to decay (but see Horoufchin, Philipp, & Koch, 2011). Importantly, extension of the RCI does not affect task-specific preparation, as task presentation is randomized so participants are unaware of the upcoming task during this period. In this paradigm, the RSI—still defined as the time between the response on the previous trial and the stimulus for the next trial—is not manipulated directly but rather is a byproduct of CSI and/or RCI manipulations. This empirical isolation of RCI and CSI highlights that the alternating runs' main manipulation of the RSI is an inseparable synthesis of RCI and CSI. Thus, the cuing paradigm provides the researcher with greater control over preparation time.

Meiran (1996) manipulated the CSI while keeping the RSI constant (which controls the degree of proactive interference from the preceding trial; see Chapter 3, this volume, for more detail on this manipulation) and found significant reductions in switch cost at extended preparation intervals, consistent with a reconfiguration account. Note this finding is inconsistent with a TSI account, which predicts equivalent performance in conditions with constant RSI. However, despite examining preparation intervals of up to 1,908 ms (see Experiment 5), a significant residual switch cost remained. Meiran et al. (2000) suggested this residual cost reflected a contribution of interference from the preceding trial exerting itself (i.e., TSI), suggesting that both reconfiguration *and* TSI contribute to the switch cost.

Meiran et al. (2000) examined this hypothesis by varying the RCI while holding the CSI constant; holding the CSI constant between conditions equates the opportunity for preparation. Variation of the RCI is thought to manipulate the degree of interference from the previous trial: Short RCIs present a cue for the next trial while the previous task is assumed to still be very active, thus leading to greater interference than a condition with a long RCI, which allows the previous task's activation to decay, leading to reduced interference. Meiran et al. found reduced switch cost at longer RCIs, suggesting TSI can account for a portion of the switch cost. Based on these results, Meiran et al. suggested the switch cost consists of three components: (a) an active preparatory process (i.e., task set reconfiguration) that sets the system for a change of task, (b) passive decay of the activation levels of previous (irrelevant) tasks, and (c) a residual component.

Although it might seem that only the preparatory component should be of interest to researchers of cognitive control, all three components are tightly linked to task set preparation (and, hence, cognitive control). For example, it has already been mentioned that the residual component has been hypothesized to arise from failure to deploy preparatory processes (and, hence, cognitive control; De Jong, 2000; Nieuwenhuis & Monsell, 2002; but see Verbruggen, Liefooghe, Vandierendonck, & Demanet, 2007). In addition, interference from the preceding task's activation may be overcome by cognitive control processes (e.g., Logan, 2003) such as inhibition, which serves to reduce the interfering activation (Grange & Houghton, 2010b; Houghton et al., 2009; Koch, Gade, Schuch, & Philipp, 2010; see also Chapter 7, this volume).

Inhibition in Task Switching

Despite the concept of behavioral inhibition in cognitive psychology being rather controversial (see, for example, Gorfein & Brown, 2007; MacLeod, Dodd, Seard, Wilson, & Bibi, 2003; Nigg, 2000; Tipper, 2001), the evidence for inhibitory control being required during task switching is compelling. Recall that the TSI hypothesis of Allport and colleagues (Allport et al., 1994; Allport & Wylie, 2000; Wylie & Allport, 2000) suggested that the switch cost was caused not only by the persistent activation of the irrelevant task but also by the persisting inhibition of the relevant task. However, Mayr and Keele (2000) were the first to provide definitive evidence for inhibition in task switching. They contrasted two types of task switching sequence: an AB*A* sequence required performing a task recently performed after one intervening trial; this was compared with a CBA sequence, where task A has not been performed so recently. The idea is that—in an ABA sequence—switching from task A to task B requires activation of B, together with inhibition of task A; if task A is inhibited, it should take longer to reactivate when it is required soon after. In contrast, in a CBA sequence, task A has not been inhibited recently and should therefore be relatively easy to activate. Across several experiments (and many replications since; see Koch et al., 2010, and Gade et al., Chapter 7, this volume), it was shown that ABA sequences do elicit a slower RT than CBA sequences. This effect was called *backward inhibition* by Mayr and Keele (2000), but the more theoretically neutral term *n–2 repetition cost* is preferred today (Koch et al., 2010).

Note that this n–2 repetition cost is not congruent with the notion that task switching merely requires activating the relevant task (e.g., Altmann & Gray, 2008), as this would produce an ABA *benefit* as task A's activation will persist and prime performance (Grange, Juvina, & Houghton, 2013). Thus, this cost is the best evidence for a role for inhibitory processes in aiding task switching. Inhibition and activation together provide an elegant solution to the stability–flexibility dilemma mentioned at the outset of this chapter: *Stability* of a task's representation is achieved by maintaining its activation; *flexibility* is achieved by inhibiting tasks once a switch is required.

Problems With the Cuing Paradigm

Although the cuing paradigm remains perhaps the most popular choice among researchers interested in cognitive control, there are a number of important limitations of the paradigm. The first is that it typically confounds task switching with *cue switching*, and the second is that RTs conflate cue-related processes and target-related processes (e.g., Altmann & Gray, 2008).

Confounding Task Switching and Cue Switching

A fundamental shortcoming of the cuing paradigm with one cue per task is that task switching and cue switching are confounded: A task switch is always coupled with a cue switch (e.g., odd/even—*low/high*) and a task repetition with a cue repetition (odd/even—*odd/even*). A solution to this issue is to use two cues per task, which creates three possible sequences: *Cue repetition* (both the cue and the task repeat), *cue switch* (the cue switches, but the task required repeats, e.g., low/high—*magnitude*), and *task switch* (both the cue and the task switches, e.g., low/high—odd/even). The contribution of cue switching to the switch cost can now be estimated by comparing cue repetition RTs with cue switch RTs; "true" task switching costs (i.e., independent of cue switch effects) can now be estimated by comparing cue switch RT with task switch RT (Logan & Bundesen, 2003; Mayr & Kliegl, 2003). Costs associated with switching cues have been reliably shown to be substantial, due to residual priming of cue encoding processes during cue repetitions (Grange & Houghton, 2010a; Logan & Bundesen, 2003; Mayr & Kliegl, 2003); cue switches do not benefit from direct priming and thus must be encoded fully. However, the task switch cost has been found to be less reliable than previously thought. Some studies find that task switches show a cost which cannot be explained by switching cues (Altmann, 2006; Arrington, Logan, & Schneider, 2007; Grange & Houghton, 2010a; Jost et al., 2008; Mayr & Kliegl, 2003; Monsell & Mizon, 2006), while others report that task switches are just as costly as cue switches (Arrington & Logan, 2004a; Logan & Bundesen, 2003, 2004; Logan & Schneider, 2006b; Schneider & Logan, 2005).

Indeed, Logan and colleagues have presented this latter finding as evidence that explicit cuing paradigms do not measure cognitive control processes. They suggest that the same processes are deployed on switch trials as on repetition trials (cf. reconfiguration theories, which state reconfiguration is deployed on switch trials, but not on repetition trials): All that is required for successful performance is to encode the cue in short-term memory (STM), encode the target, and use this cue–stimulus compound to probe long-term memory (LTM) for the correct response. For example, after practice, the cue "odd/even" and the stimulus "2" uniquely retrieve the response "even" from LTM. From this perspective, task switching is merely cue switching: Cue switches (and also task switches) require encoding of a new cue into STM, which takes time. Cue repetition trials benefit from priming of STM contents (as the relevant cue is already encoded), whereas cue switch and task switch trials require encoding a new cue into STM; this theory was formalized mathematically by Schneider and Logan (2005; see also Logan & Schneider, 2010, and Schneider & Logan, 2009; see Chapter 8, this volume, for more detail about these models). Note this theory predicts identical performance for cue switch and task switch trials (which was indeed what Logan & Budnesen, 2003, reported); however, more recent evidence has suggested cue switch and task switch performance can be dissociated behaviorally (Arrington et al., 2007; Grange & Houghton, 2010a; Mayr & Kliegl, 2003) and at the neural level (Jost et al., 2008).

Mayr and Kliegl (2003) suggested that the cue switch cost arises from priming of a cue-specific retrieval route that obtains task rules from LTM and installs them into working memory. By this theory, when a cue repeats, the retrieval route is primed, contra to when a cue switches, which requires the use of a new (and unprimed) retrieval route. Thus, cue switch costs arise from priming of control processes that establish a working memory representation of what to do. Grange and Houghton (2010a) also provided evidence that cue switch costs arise from cognitive control processes responsible for establishing a working memory representation of what to do.

Although the cue switch–versus–task switch area of research has become incredibly controversial over recent years, the cuing paradigm remains a powerful tool for researchers of cognitive control, if used with the above constraints in mind. Meiran (Chapter 3, this volume) provides an excellent "recipe" for researchers interested in using this paradigm.

Separating Cue-Related Processes From Target-Related Processes

Performance on the standard explicit cuing paradigm—i.e. responses to unitary stimuli following a valid task cue—is a combination of cue-related processing and target-related processing; thus performance differences could be due to changes in cue processing or target processing (or a mixture of both). Although cue-related and target-related processes can be separated theoretically (e.g., see the mathematical models of Logan & Bundesen, 2003, and Schneider & Logan, 2005), empirical separation would be beneficial.

The work of Altmann has championed one such empirical paradigm that allows such separation (Altmann, 2002, 2006, 2007; Altmann & Gray, 2002, 2008; see also Chapter 5, this volume). This *extended runs paradigm* presents a cue that signals which of two (or more) tasks is relevant for a given "run." On this run, the cue is only presented with the first target; after this, targets are presented in isolation, and the relevant task must be maintained in memory (e.g., C_AAAAA where C_x is the cue for task x). Cues can either indicate a repetition of the previously relevant task (e.g., C_AAAAA—C_AAAAA) or a switch from the previous task (e.g., C_AAAAA—C_BBBBB). Using this paradigm, only trial one conflates cue-processing with target-processing, whereas uncued trials only reflect target processing.

Typical findings from this paradigm largely mirror those found in the standard cuing paradigm on trial one of the run (i.e., the cued trial); for example, switch RTs are slower than repetition RTs. However, there are some findings that are unique to this paradigm. For example, if the cue signals a repetition of the previous task, trial one RT is much larger than the RT for cueless trials, indicating a substantial cost of processing the cue independent of any switch of task. This *restart cost* (Allport & Wylie, 2000; Altmann, 2002, 2006, 2007; Altmann & Gray, 2002, 2008; Gopher Armony, & Greenshpan, 2000; Poljac et al., 2009) is thought to reflect the time the cognitive system needs to reactivate task representations that may have decayed since the last cue presentation. The restart cost is important theoretically, as it suggests that encoding and activation processes are run on repetition trials as well as switch trials (a view formalized by Altmann & Gray, 2008; see also Chapter 5, this volume), a view not compatible with a reconfiguration view of a dedicated set of processes that run on switch trials only (Meiran, 1996; Rogers & Monsell, 1995). It suggests the cognitive system faces the same problem on switch trials *and* repetition trials of ensuring the relevant task is the most active among all competing representations (see Chapters 5 and 8, this volume, for more information about this).

A related finding is that RTs slow steadily over a run of cueless trials (Altmann, 2002, Altmann & Gray, 2002, 2008). This *within-run slowing* is theorized to reflect the system attempting to access a decaying task representation (which becomes more difficult over time due to passive decay, and hence slows responses); the restart cost is thought to reflect the time needed to reactivate the decayed representation on repetition runs.

Newer Paradigms

Due to the problems inherent with the explicit cuing paradigm—and due to the growing consensus that it is not sensitive enough to measure cognitive control processes (Logan, 2003)—researchers have begun to investigate alternative paradigms capable of capturing cognitive control processes in operation. Such alternatives are briefly discussed below.

The *transition-cuing paradigm*, in which cues are presented that merely inform participants whether to "switch" or "repeat" tasks; that is, the participant must retain in memory the currently relevant task so that the next transition cue can be interpreted and acted on appropriately. This paradigm—introduced by Forstmann, Brass, and Koch (2007; but see Rushworth, Hadland, Paus, & Sipila, 2002)—thus allows the examination of potentially more "high-level" control in operation (Jost, De Baene, Koch, & Brass, 2013). Among the paradigm's immediate appeal is that the cues used are themselves not tied to one particular task (cf. standard task cues) but are merely associated with transition requirements; thus, the cues are signaling the required behavior and cannot—*prima facie*—be used in conjunction with the stimulus to drive compound-cue retrieval of the response from LTM (although see Schneider & Logan, 2007b, for how this might be achieved in conjunction with mediator retrieval—the process of retrieving a meaningful task name in response to a nontransparent cue, Logan & Schneider, 2006a). In addition, transition cuing also allows the occurrence of a task switch being signaled by a cue repetition (e.g., "Switch" → "Switch"), which is not possible with the standard 2:1 cue–task mapping procedure. Although there remain methodological issues to overcome (see, e.g., Schneider & Logan, 2007b), it seems that transition cuing is an interesting—and, as yet, relatively unexplored—avenue with which to research cognitive control.

The *task-span procedure*—introduced by Logan (2004; see also Logan, 2006)—ensures that cognitive control is being used during task switching by having participants remember a short list of task names (e.g., parity—parity—magnitude—parity—magnitude—magnitude. . .) and then execute these tasks on stimuli that follow (e.g., 6—7—2—9—8—6. . .). As a consequence of such lists, some responses will be task repetitions (responses 2 and 6 in the example) and some will be task switches (responses 3, 4, and 5). This procedure is thought to require cognitive control as the participant must control access to memory elements so as to retrieve the correct task name on the current trial, as well as implementing task switches should the need arise (Logan, 2006). However, it is possible that the task names recalled could be used to drive compound-cue retrieval (Logan & Schneider, 2010), so, although certainly interesting—especially if one is interested in exploring the relationship between the processes dedicated to task switching and the processes dedicated to working memory maintenance/access—the task-span procedure might face the same problems as the explicit cuing paradigm (Mayr, 2010). As this paradigm is still relatively underresearched, further work is required to establish whether the task-span procedure shares the explicit-cuing paradigm's fate.

Leading the way in the endeavor of finding an alternative paradigm is the work of Arrington and colleagues, who developed the *voluntary task switching (VTS) paradigm* (Arrington & Logan, 2004b; see Chapter 6, this volume). In this paradigm, no cues are presented to participants (which immediately alleviates the problem of cue switching), but rather participants must choose which of two (or more; see Lien & Ruthruff, 2008) tasks to perform on a random basis. Presented with a stimulus on an experimental trial, participants are typically instructed to choose which task to perform as if flipping a coin decided the outcome; so, on some trials participants will be switching from the task they performed on the previous trial, and on some trials they will be repeating the task they performed on the previous trial. By separating the responses for the two tasks to separate hands (i.e., respond with the left hand using the "D" and "F" keys if performing task A, and respond with the right hand using the "J" and "K" keys if performing task B), the researcher is able to easily establish which task was attempted by the participant. As task choices require cognitive control (see Chapter 6, this volume), it is thought that the VTS paradigm might capture these active processes during performance (see Arrington & Logan, 2004, 2005). Together with standard dependent variables typical to task switching—RTs and error rates to task repetitions and to task switches—VTS paradigms introduce a unique dependent variable, that of the probability of choosing a task repetition [*p*(repetition)]. *P*(repetition) should be.5 if the task choice truly is random (as task repetitions should be just as frequent as task switches), yet research has consistently shown a *repetition bias* (Chapter 6, this volume), hinting at some fundamental limitation in choosing task switches compared with task repetitions. This *p*(repetition) can be used to investigate what factors influence task choice. Although choice in the VTS is under some degree of top-down control, several studies have shown that exogenous, bottom-up factors can influence task choice (e.g., Arrington, 2008; Arrington &

Rhodes, 2010; Arrington, Weaver, & Pauker, 2010; Butler, Arrington, & Weywadt, 2011; Demanet, Verbruggen, Liefooghe, & Vandierendonck, 2010; Mayr & Bell, 2006; Yeung, 2010), suggesting there might be some limitation to the belief that VTS paradigms completely capture top-down processing. However, the paradigm appears to be an increasingly popular tool with which to explore cognitive control during task switching.

CONCLUSION AND OVERVIEW OF CHAPTERS

Even though this chapter intends to provide merely a *broad* overview of the main trends in task switching research, the reader would be right to be already forming the impression that the task switching field is deep and expansive, with a plethora of clever empirical designs and comprehensive theoretical advances. The present volume brings together experts across the wide field of task switching research, with chapters dedicated to each author's subdomain of expertise. It is hoped that this volume will aid consolidation of knowledge gleaned from research efforts so far and highlight important areas for future research. Here, we provide an overview of the chapters that make up this volume. We had originally planned to end the book with a chapter on future directions for research on task switching and cognitive control. However, all of the authors have done a superb job of highlighting important areas in each of their respective topics that deserve more attention in future research; as such, the reader will find an abundance of important and unresolved questions that need attention.

In Chapter 2, **Schneider and Logan** discuss the important—but often neglected—topic of what actually constitutes a task; coupled with this, it has long been suggested that task switching requires implementing a task set (e.g., Jersild, 1927; Rogers & Monsell, 1995), but the nature of the task set itself often goes unspecified. How can we tell whether task set reconfiguration has occurred if we are not clear on what a task set really is? At first glance, what constitutes a task seems simple, but Schneider and Logan argue that task switching research—and its associated theorizing—has been hampered by poor definitions of what are tasks and task sets. Schneider and Logan provide an elegant distinction between the two: A task is the representation of a set of instructions required to perform an activity accurately; a task set is the set of representations and processes that enable execution of the task. Schneider and Logan argue that—contrary to the often-held assumption that switching between two tasks in a task switching paradigm requires switching between two task sets—tasks and task sets do not necessarily have a one-to-one mapping. The authors provide recommendations for how to explore the nature of the relationship between tasks and task sets.

In Chapter 3, **Meiran** provides a user's guide for using the explicit-cuing paradigm, arguably the most popular choice among researchers interested in cognitive control. As stated in this introductory chapter, there are many issues that a researcher new to the area needs to be aware of when using this paradigm; with this user guide, researchers are treated to excellent recommendations for designing a task switching study, answering important questions such as "How many tasks should I use?" "How should I estimate mixing cost?" "What cues should I use?" "How do I empirically separate the retrievability of the previous task and the preparation for the current task?" This chapter also has a section on what actually constitutes a task (cf. Schneider & Logan, this volume); thus, this topic is clearly gaining traction in the minds of researchers. Closely following the recommendations set out in this chapter will allow researchers to produce valid experimental procedures capable of tapping important cognitive control processes.

In Chapter 4, **Marí-Beffa and Kirkham** provide an overview of the mixing cost, the finding of increased RTs to task repetitions in mixed blocks than in pure blocks. The chapter reviews current work and major findings regarding this cost and discusses key methodological difficulties in measuring it (together with some practical recommendations for the reader). Marí-Beffa and Kirkham take this cost to be indicative of sustained mental control processes that are activated when participants expect to have to switch between task sets; as such, the mixing cost is an interesting effect with which to explore cognitive control processes.

Chapter 5 provides an overview of the empirical and theoretical advantages of using the extended-runs paradigm. As **Altmann** highlights, this paradigm allows separation of cue-related processes and stimulus-related processes on performance; this separation (and the associated effects) highlights important constraints on models of cognitive control during task switching. In this chapter, Altmann discusses these effects in relation to his recent model of task switching (Altmann & Gray, 2008; see also Chapter 8 this volume).

In Chapter 6, **Arrington, Reiman, and Weaver** provide an excellent overview of one of the newest variants of task switching paradigms, the VTS paradigm. Although in its relative infancy as a paradigm, the VTS procedure has garnered considerable interest among researchers, and a wealth of empirical investigation has already accumulated. The promise is that this paradigm captures nuances of cognitive control not measurable with other task switching paradigms, such as control over task choice. Arguably, this puts task switching research into more "ecologically valid" scenarios: In everyday life, humans often take control over which task to execute at a given moment rather than being instructed to do so; the VTS aims to uniquely capture the processes that give rise to volitional behavior. This chapter provides an overview of the empirical contributions, as well as detailed discussion of the theoretical accounts of VTS performance; open questions in this important area of research are also highlighted, providing fruitful avenues for the next wave of research.

In Chapter 7, **Gade, Schuch, Druey, and Koch** provide a comprehensive overview of inhibitory control during task switching. Inhibition has become an increasingly controversial concept in cognitive psychology (Gorfein & Brown, 2007; MacLeod, Dodd, Seard, Wilson, & Bibi, 2003; Nigg, 2000; Tipper, 2001), but there is convincing evidence for a robust role for inhibitory mechanisms during task switching; this makes the task switching paradigm an ideal vehicle to explore inhibitory control in typical and atypical populations. The authors discuss two lines of evidence for inhibition in task switching: Response repetition effects and the n–2 repetition cost, with the latter being the least ambiguous line of evidence. There is convincing evidence—reviewed in this chapter—that inhibition is a flexible process targeting whichever aspect of the trial structure (cue, target, response) that generates interference when the task switches (Houghton et al., 2009); however, the exact nature of the inhibitory input itself (is it lateral inhibition? is it self-inhibition?) remains largely unclear. This area remains a fertile ground for research, and Gade and colleagues highlight many unanswered questions requiring researchers' attention going forward.

In Chapter 8, **Grange and Houghton** provide an overview of the key models of cognitive control during task switching. Models of cognition allow researchers to peer inside the "black box" that is human cognition. Thus, models of task switching allow researchers to investigate and test formal theories of how cognitive control is deployed to allow efficient goal-directed behavior in multitask environments. This chapter reviews the most influential and successful models of task switching. We provide an overview of the architecture of each model, before discussing how each model explains key theoretical and empirical concepts that have accumulated in the field of task switching. In a final section, we discuss critical general shortcomings of extant models and propose some promising future directions for modeling efforts. In particular, we note that the formal modeling of inhibitory processes in task switching—a process with considerable empirical support—is a notable omission from many models and is an essential area for future research.

Chapter 9 marks the start of the second section, focusing on neuroscientific examination of cognitive control during task switching. In this chapter, **Karayanidis and Jamadar** review the electrophysiological evidence, focusing on event-related potentials (ERPs). ERPs provide the researcher with superb temporal resolution, tracking neural activity at the scalp with millisecond precision. As behavioral measures (e.g., RTs) usually only collect a response from the subject at the end of a sequence of events (e.g., an experimental trial in task switching, which consists of task cues and stimuli), inferences about the participant's responses to the various components of the trial are inevitably somewhat indirect. The use of ERP recording, on the other hand, allows the collection of electrophysiological measures through an experimental trial, whether or not a participant makes an overt response. The high temporal resolution of these methods mean that it is feasible to separate out the brain responses to events occurring within less than 100 ms of each other. Hence, for instance, brain responses to task cues can be separated from those to stimuli, and the effects of task switching manipulations on the various components of a trial structure can be separated. Thus, ERPs allow an unprecedented examination as to the time-course of cognitive control during task switching.

In this chapter, **Karayanidis and Jamadar** review the ERP evidence of proactive and reactive control during task switching. Proactive control refers to processes deployed during preparatory intervals in task switching, which ready the system for the upcoming task; reactive control refers to control processes that serve to reduce interference during stimulus onset. The evidence reviewed leads the authors to suggest that proactive control requires general task preparation (i.e., not specific to switching) and switch-specific preparation (i.e., dedicated processes that only run on switch trials). In terms of reactive control, the evidence suggests switch-specific modulation of response preparation and response implementation. The chapter also provides coverage of multi-modal studies which mix ERP measurements with other neuroscientific techniques.

In Chapter 10, **Richter and Yeung** provide an overview of functional magnetic resonance imaging (fMRI) studies of task switching. The advent of noninvasive neuroimaging techniques with high spatial resolution has had a tremendous and continuing impact on cognitive psychology, and task switching is being extensively studied using (usually) event-related fMRI designs. While not enjoying the temporal resolution of ERPs, fMRI provides a high degree of spatial resolution, allowing the brain areas involved in the maintenance and switching of task rules to be investigated. In this chapter, the authors provide a meta-analysis of 34 fMRI task switching studies to elucidate the neural regions responsible for task switching. In addition, the authors continually refer to how evidence from fMRI studies shapes and constrains our theorizing of cognitive control in task switching. One striking conclusion from this chapter is that there is very little evidence from the studies reviewed that switch-specific (i.e., reconfiguration) processes are recruited during task switching.

In Chapter 11, **Das and Wylie** review the effect of executive dysfunction on task switching performance. As task switching is generally thought to require recruitment of cognitive control processes, it is an excellent paradigm with which to explore the broader domain of executive functioning in atypical populations. Das and Wylie examine the current literature on task switching and executive dysfunction, focusing on stroke, Parkinson disease, Huntington disease, traumatic brain injury, and schizophrenia. Exploring a range of executive dysfunction populations allows the authors to elucidate to what extent the disorders differentially affect cognitive control in task switching (with some populations showing surprising "sparing" of task switching ability). The investigation of neurological pathology complements the work of neuroimaging, which can only be taken so far; for example, demonstrating activation of region X in an fMRI study cannot differentiate whether the activation in region X is a cause or a consequence of a particular cognitive process. Finding patients with damage to region X—and investigating their performance on task switching—can bridge the gap between research on healthy and atypical populations in elucidating the neural underpinnings of task switching.

In Chapter 12, **Ravizza and Salo** review the literature on task switching in psychiatric disorders. As many psychiatric disorders are associated with deficits in executive function, and task switching is thought to require executive control, these populations become an important area for investigation. In this chapter, the authors review evidence from task switching studies in four populations: schizophrenia, autism spectrum disorder, attention-deficit/hyperactivity disorder, and major depression. There exist dissociable processes during task switching that are selectively affected by some disorders and not others, constraining both theoretical models of task switching and models of the effects of clinical disorders on cognition.

Chapter 14 focuses on cognitive flexibility in childhood and adolescence. In this chapter, **Peters and Crone** review the behavioral and neural development of two types of cognitive flexibility: instructed flexibility (more typically measured by the standard task switching paradigm) and adaptive flexibility (measured with performance-monitoring paradigms). Both approaches provide insights into resolution of the stability–flexibility dilemma. Studying the development of cognitive control during childhood provides important insights, as the neural architecture thought to serve cognitive control (e.g., the frontal lobes) is not fully developed in adolescence. By reviewing the evidence, the authors conclude that both types of flexibility are dissociable when comparing adults with typically developing children, and provide ideas for future research.

Chapter 15 focuses on the effect of healthy aging on task switching performance. In a world where the average life expectancy is consistently rising, the implications of healthy aging on cognitive performance are becoming more germane. In this chapter, **Kray and Ferdinand** review the literature on task switching and aging, concentrating their discussion on three focused areas: To what extent are there process-specific limitations of older adults in task switching (e.g., impairments of task maintenance and selection)? Which factors module age-related impairments in these processes? Which cognitive interventions are useful for improving them.

NOTES

1. All searches conducted in PsycINFO on August 8, 2013.
2. There is a sixth, but it only applies to multistep procedures that are not discussed in this chapter (but see Luria & Meiran, 2003, 2006; Schneider & Logan, 2006a).

REFERENCES

Ach, N. On volition (T. Herz, Trans.). (Original work published 1910) Available at: University of Konstanz, Cognitive Psychology Web site: http://www.uni-konstanz.de/kogpsych/ach.htm. 2006.

Allport, A., Styles, E. A., & Hsieh, S. (1994). Shifting intentional set: Exploring the dynamic control of tasks. In C. Umilta & M. Moscovitch (Eds.), *Attention and performance XV: Conscious and nonconscious information processing* (pp. 421–452). Cambridge, MA: MIT Press.

Allport, A., & Wylie, G. R. (2000). Task switching, stimulus–response bindings, and negative priming. In S. Monsell & J. Driver (Eds.), *Control of cognitive processes: Attention and performance XVIII* (pp. 35–70). Cambridge, MA: MIT Press.

Altmann, E. M. (2002). Functional decay of memory for tasks. *Psychological Research*, *66*, 287–297.

Altmann, E. M. (2003a). Task switching and the pied homunculus: Where are we being led? *Trends in Cognitive Sciences*, *7*, 340–341.

Altmann, E. M. (2003b). Think globally, ask functionally. *Behavioral & Brain Sciences*, *26*, 602–603.

Altmann, E. M. (2006). Task switching is not cue switching. *Psychonomic Bulletin & Review*, *13*, 1016–1022.

Altmann, E. M. (2007). Comparing switch costs: Alternating runs and explicit cuing. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *33*, 475–483.

Altmann, E. M., & Gray, W. D. (2002). Forgetting to remember: The functional relationship of decay and interference. *Psychological Science*, *13*, 27–33.

Altmann, E. M., & Gray, W. D. (2008). An integrated model of cognitive control in task switching. *Psychological Review*, *115*, 602–639.

Arbuthnott, K. D. (2008a). Asymmetric switch cost and backward inhibition: Carryover activation and inhibition in switching between tasks of unequal difficulty. *Canadian Journal of Experimental Psychology*, *62*, 91–100.

Arrington, C. M. (2008). The effect of stimulus availability on task choice in voluntary task switching. *Memory & Cognition*, *38*, 991–997.

Arrington, C. M., & Logan, G. D. (2004a). Episodic and semantic components of the compound stimulus strategy in the explicit task cuing procedure. *Memory & Cognition*, *32*, 965–976.

Arrington, C. M., & Logan, G. D. (2004b). The cost of a voluntary task switch. *Psychological Science*, *15*, 610–615.

Arrington, C. M., & Logan, G. D. (2005). Voluntary task switching: Chasing the elusive homunculus. *Journal of Experimental Psychology: Learning, Memory and Cognition*, *31*, 683–702.

Arrington, C. M., Logan, G. D., & Schneider, D. W. (2007). Separating cue encoding from target processing in the explicit task-cuing procedure: Are there “true” task switch effects? *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *33*, 484–502.

Arrington, C. M., & Rhodes, K. M. (2010). Perceptual asymmetries influence task choice: The effect of lateralized presentation of hierarchical stimuli. *Laterality*, *15*, 501–513.

Arrington, C. M., Weaver, S. M., & Pauker, R. L. (2010). Stimulus-based priming of task choice during voluntary task switching. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *36*, 1060–1067.

Baddeley, A., Chincotta, D., & Adlam, A. (2001). Working memory and the control of action: Evidence from task switching. *Journal of Experimental Psychology: General*, *130*, 641–657.

Bryck, R. L., & Mayr, U. (2005). On the role of verbalization during task set selection: switching or serial order control? *Memory & Cognition*, *33*, 611–623.

Butler, K.M., Arrington, C.M., & Weywadt, C. (2011). Working memory capacity modulates task performance but has little influence on task choice. *Memory & Cognition*, *39*, 708–724.

De Jong, R. (2000). An intention-activation account of residual switch costs. In S. Monsell & J. Driver (Eds.), *Attention and performance XVIII: Control of cognitive processes* (pp. 357–376). Cambridge, MA: MIT Press.

Demanet, J., Verbruggen, F., Liefooghe, B., Vandierendonck, A. (2010). Voluntary task switching under load: Contribution of top-down and bottom-up factors in goal-directed behavior. *Psychonomic Bulletin & Review*, *3*, 387–393.

Dreisbach, G. (2012). Mechanisms of cognitive control: The functional role of task rules. *Current Directions in Psychological Science*, *21*, 227–231.

Dreisbach, G., & Haider, H. (2008). That's what task sets are for: Shielding against irrelevant information. *Psychological Research*, *72*, 355–361.

Dreisbach, G., & Haider, H. (2009). How task representations guide attention: Further evidence for the shielding function of task sets. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *35*, 477–486.

Emerson, M. J., & Miyake, A. (2003). The role of inner speech in task switching: A dual-task investigation. *Journal of Memory and Language*, *48*, 148–168.

Forstmann, B. U., Brass, M., & Koch, I. (2007). Methodological and empirical issues when dissociating cue-related from task-related processes in the explicit task-cuing procedure. *Psychological Research*, *71*, 393–400.

Gilbert, S. J., & Shallice, T. (2002). Task switching: A PDP model. *Cognitive Psychology*, *44*, 297–337.

Gopher, D., Armony, L., & Greenshpan, Y. (2000). Switching tasks and attention policies. *Journal of Experimental Psychology: General*, *129*, 308–339.

Gorfein, D. S., & Brown, V. R. (2007). Saying no to inhibition. In D. S. Gorfein & C. M. MacLeod (Eds.), *Inhibition in cognition* (pp. 103–124).

Goschke, T. (2000). Intentional reconfiguration and involuntary persistence in task set switching. In S. Monsell & J. Driver (Eds.), *Control of cognitive processes: Attention and performance* (Vol. 18, pp. 331–355). Cambridge, MA: MIT Press.

Grange, J. A., & Houghton, G. (2010a). Cue-switch costs in task-switching: Cue priming or control processes? *Psychological Research*, *74*, 481–490.

Grange, J. A., & Houghton, G. (2010b). Heightened conflict in cue–target translation increases backward inhibition in set switching. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *36*, 1003–1009.

Grange, J. A., Juvina, I., & Houghton, G. (2013). On costs and benefits of n–2 repetitions in task switching: towards a behavioural marker of cognitive inhibition. *Psychological Research*, *77*, 211–222.

Houghton, G., Pritchard, R., & Grange, J. A. (2009). The role of cue–target translation in backward inhibition of attentional set. *Journal of Experimental Psychology: Learning, Memory and Cognition*, *35*, 466–476.

Horoufchin, H., Philipp, A. M., & Koch, I. (2011). The dissipating task-repetition benefit in cued task switching: Task-set decay or temporal distinctiveness? *Journal of Experimental Psychology: Human Perception and Performance*, *37*, 455–472.

Jersild, A. T. (1927). *Mental set and shift. Archives of Psychology*, *89*(entire issue).

Jost, K., De Baene, W., Koch, I., & Brass, M. (2013). A review of the role of cue processing in task switching. *Zeitschrift für Psychologie*, *221*, 5–14.

Jost, K., Mayr, U., & Rosler, F. (2008). Is task switching nothing but cue priming? Evidence from ERPs. *Cognitive, Affective, and Behavioral Neuroscience*, *8*, 74–84.

Kiesel, A., Steinhauser, M., Wendt, M., Falkstein, M., Jost, K., Philipp, A., & Koch, I. (2010). Control and interference in task switching—a review. *Psychological Bulletin*, *136*, 849–874.

Koch, I., Gade, M., Schuch, S., & Philipp, A. M. (2010). The role of inhibition in task switching—A review. *Psychonomic Bulletin & Review*, *17*, 1–14.

Lhermitte, F. (1983). Utilization behaviour and its relation to the frontal lobes. *Brain*, *106*, 237–255.

Lien, M.-C., & Ruthruff, E. (2008). Inhibition of task set: Converging evidence from task choice in the voluntary task-switching paradigm. *Psychonomic Bulletin & Review*, *15*, 1111–1116.

Lien, M.-C., Ruthruff, E., Remington, R. W., & Johnston, J. C. (2005). On the limits of advance preparation for a task switch: Do people prepare all the task some of the time or some of the task all the time? *Journal of Experimental Psychology: Human Perception and Performance*, *31*, 299–315.

Logan, G. D. (2003). Executive control of thought and action: In search of the wild homunculus. *Current Directions in Psychological Science*, *12*, 45–48.

Logan, G. D. (2004). Working memory, task switching, and executive control in the task span procedure. *Journal of Experimental Psychology: General*, *133*, 218–236.

Logan, G. D. (2006). Out with the old, in with the new: More valid measures of switch cost and retrieval time in the task span procedure. *Psychonomic Bulletin & Review*, *13*, 139–144.

Logan, G. D., & Bundesen, C. (2003). Clever homunculus: Is there an endogenous act of control in the explicit task-cuing procedure? *Journal of Experimental Psychology: Human Perception and Performance*, *29*, 575–599.

Logan, G. D., & Bundesen, C. (2004). Very clever homunculus: Compound stimulus strategies for the explicit task-cuing procedure. *Psychonomic Bulletin & Review*, *11*, 832–840.

Logan, G. D., & Gordon, R. D. (2001). Executive control of visual attention in dual-task situations. *Psychological Review*, *108*, 393–434.

Logan, G. D., & Schneider, D. W. (2006a). Interpreting instructional cues in task switching procedures: The role of mediator retrieval. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *32*, 347–363.

Logan, G. D., & Schneider, D. W. (2006b). Priming or executive control? Associative priming of cue encoding increases "switch costs" in the explicit task-cuing procedure. *Memory & Cognition*, *34*, 1250–1259.

Logan, G. D., & Schneider, D. W. (2010). Distinguishing reconfiguration and compound-cue retrieval in task switching. *Psychologica Belgica*, *50*, 413–433.

Los, S. A. (1996). On the origin of mixing costs: Exploring information processing in pure and mixed blocks of trials. *Acta Psychologica*, *94*, 145–188.

Luria, R., & Meiran, N. (2003). Online order control in the psychological refractory period paradigm. *Journal of Experimental Psychology: Human Perception and Performance*, *29*, 556–574.

Luria, R., & Meiran, N. (2006). Dual route for subtask order control: Evidence from the Psychological Refractory Period paradigm. *Quarterly Journal of Experimental Psychology: Section A*, *59*, 720–744.

MacLeod, C. M., Dodd, M. D., Sheard, E. D., Wilson, D. E., & Bibi, U. (2003). In opposition to inhbition. *Psychology of Learning & Motivation*, *43*, 163–214.

Marí-Beffa, P., Cooper, S., & Houghton, G. (2012). Unmixing the mixing cost: Contributions from dimensional relevance and stimulus-response suppression. *Journal of Experimental Psychology: Human Perception and Performance*, *38*, 478–488.

Mayr, U. (2010). The surface structure and the deep structure of sequential control: What can we learn from task-span switch costs? *Psychonomic Bulletin & Review*, *17*, 693–698.

Mayr, U., & Bell, T. (2006). On how to be unpredictable: Evidence from the voluntary task switching paradigm. *Psychological Science*, *17*, 774–780.

Mayr, U., & Keele, S. W. (2000). Changing internal constraints on action: The role of backward inhibition. *Journal of Experimental Psychology: General*, *129*, 4–26.

Mayr, U., & Kliegl, R. (2000). Task-set switching and long-term memory retrieval. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *26*, 1124–1140.

Mayr, U., & Kliegl, R. (2003). Differential effects of cue changes and task changes on task-set selection costs. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *29*, 362–372.

Meiran, N. (1996). Reconfiguration of processing mode prior to task performance. *Journal of Experimental Psychology. Learning, Memory, and Cognition*, *22*, 1423–1442.

Meiran, N. (2010). Task switching: Mechanisms underlying rigid vs. flexible self control. In R. Hassin, K. Ochsner, & Y. Trope (Eds.). *Self control in society, mind and brain* (pp. 202–220). New York, NY: Oxford University Press.

Meiran, N., Chorev, Z., & Sapir, A. (2000). Component processes in task switching. *Cognitive Psychology*, *41*, 211–253.

Meuter, R. F. I., & Allport, A. (1999). Bilingual language switching in naming: Asymmetrical costs of language selection. *Journal of Memory and Language*, *40*, 25–40.

Monsell, S. (2003). Task switching. *Trends in Cognitive Sciences*, *7*, 134–140.

Monsell, S., & Mizon, G. (2006). Can the task-cuing paradigm measure an endogenous task-set reconfiguration process? *Journal of Experimental Psychology: Human Perception and Performance*, *32*, 493–516.

Monsell, S., Yeung, N., & Azuma, R. (2000). Reconfiguration of task-set: Is it easier to switch to the weaker task? *Psychological Research*, *63*, 250–264.

Nieuwenhuis, S., & Monsell, S. (2002). Residual costs in task switching: Testing the failure-to-engage hypothesis. *Psychonomic Bulletin & Review*, *9*, 86–92.

Nigg, J. T. (2000). On inhibition/disinhibition in developmental psychopathology: Views from cognitive and personality psychology and a working inhibition taxonomy. *Psychological Bulletin*, *126*, 220–246.

Philipp, A. M., Kalinich, C., Koch, I., & Schubotz, R. I. (2008). Mixing costs and switch costs when switching stimulus dimensions in serial predictions. *Psychological Research*, *72*, 405–414.

Poljac, E., Koch, I., & Bekkering, H. (2009). Dissociating restart cost and mixing cost in task switching. *Psychological Research*, *73*, 407–416.

Reason, J. T. (1984). Lapses of attention. In R. Parasuraman, R. Davies, & J. Beatty (Eds.), *Varieties of attention* (pp. 515–549). Orlando, FL: Academic Press.

Rogers, R. D., & Monsell, S. (1995). Costs of a predictible switch between simple cognitive tasks. *Journal of Experimental Psychology: General*, *124*, 207–231.

Rubin, O., & Meiran, N. (2005). On the origins of the task mixing cost in the cuing task-switching paradigm. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *31*, 1477–1491.

Rubinstein, J. S., Meyer, D. E., & Evans, J. E. (2001). Executive control of cognitive processes in task switching. *Journal of Experimental Psychology: Human Perception and Performance*, *27*, 763–797.

Rushworth, M. F. S., Hadland, K. A., Paus, T., & Sipila, P. K. (2002). Role of the human medial frontal cortex in task switching: A combined fMRI and TMS study. *Journal of Neurophysiology*, *87*, 2577–2592

Schneider, D. W., & Anderson, J. R. (2010). Asymmetric switch costs as sequential difficulty effects. *Quarterly Journal of Experimental Psychology*, *63*, 1873–1894.

Schneider, D. W., & Logan, G. D. (2005). Modeling task switching without switching tasks: A short-term priming account of explicitly cued performance. *Journal of Experimental Psychology: General*, *134*, 343–367.

Schneider, D. W., & Logan, G. D. (2006a). Hierarchical control of cognitive processes: Switching tasks in sequences. *Journal of Experimental Psychology: General*, *135*, 623–640.

Schneider, D. W., & Logan, G. D. (2007a). Defining task-set reconfiguration: The case of reference point switching. *Psychonomic Bulletin & Review*, *14*, 118–125.

Schneider, D. W., & Logan, G. D. (2007b). Task switching versus cue switching: Using transition cuing to disentangle sequential effects in task-switching performance. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *33*, 370–378.

Schneider, D. W., & Logan, G. D. (2009). Selecting a response in task switching: Testing a model of compound cue retrieval. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *35*, 122–136.

Spector, A., & Biederman, Y. (1976). Mental set and mental shift revisited. *American Journal of Psychology*, *89*, 669–679.

Sternberg, S. (1969). The discovery of processing stages: Extensions of Donders' method. *Acta Psychologica*, *30*, 276–315.

Stroop, J. R. (1935). Studies of interference in serial verbal reactions. *Journal of Experimental Psychology*, *18*, 643–662.

Sudevan, P., & Taylor, D. A. (1987). The cuing and priming of cognitive operations. *Journal of Exerimental Psychology: Human Perception and Performance*, *13*, 89–103.

Tipper, S. P. (2001). Does negative priming reflect inhibitory mechanisms: A review and integration of conflicting views. *Quarterly Journal of Experimental Psychology, 54A*, 321–343.

Vandierendonck, A., Liefooghe, B., & Verbruggen, F. (2010). Task switching: Interplay of reconfiguration and interference control. *Psychological Bulletin*, *136*, 601–626.

Verbruggen, F., Liefooghe, B., Vandierendonck, A., & Demanet, J. (2007). Short cue presentations encourage advance task preparation: A recipe to diminish the residual switch cost. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *33*, 342–356.

Wylie, G., & Allport, A. (2000). Task switching and measurement of "switch costs." *Psychological Research*, *63*, 212–233.

Yeung, N. (2010). Bottom-up influences on voluntary task switching: The elusive homunculus escapes. *Journal of Experimental Psychology: Learning Memory and Cognition*, *36*, 348–362.

Yeung, N., & Monsell, S. (2003). The effects of recent practice on task switching. *Journal of Experimental Psychology: Human Perception and Performance*, *29*, 919–936.

2

Tasks, Task Sets, and the Mapping Between Them

DARRYL W. SCHNEIDER AND GORDON D. LOGAN

INTRODUCTION

The copious research on task switching over the past several years has been fueled by the belief that understanding how people switch tasks will shed light on the broader question of how the mind exercises control over cognition. However, the hodgepodge of empirical phenomena (for reviews, see Kiesel et al., 2010; Vandierendonck, Liefooghe, & Verbruggen, 2010) and the lack of theoretical integration in the task switching domain lead one to wonder how much light has actually passed through the semiopaque window of task switching. We contend that the opacity is a consequence of fundamental inadequacies in how researchers think about and discuss task switching. *Tasks* and *task sets* (the means by which tasks are performed) are often poorly defined, and the mapping between them is usually given superficial analysis. As a result, it is difficult to link theory to data and to determine when and how the cognitive control purportedly reflected by task switching is being exercised. Our goal in this chapter is to draw attention to these issues in an effort to stimulate critical thinking about key concepts in task switching research and facilitate progress toward achieving a better understanding of cognitive control.

WHAT IS A TASK?

> "We acknowledge that it is difficult to define with precision, even in the restricted context of discrete reaction tasks, what constitutes a 'task.' "
>
> —Rogers and Monsell *(1995, p. 208)*

The difficulty of defining a task was recognized early by Rogers and Monsell (1995), but since then it has largely been ignored. We think part of the reason the issue has been neglected is that researchers are free to call anything a "task" and, by extension, refer to even the smallest of transitions as "task switching." For example, consider an experiment in which subjects learn a simple pair of stimulus–response mappings (e.g., press key *1* for stimulus *A* and key *2* for stimulus *B*) then perform trials on which they see either an *A* or a *B* displayed in either green or red font. When the stimulus is green, they have to respond according to the learned mapping, but when the stimulus is red, they have to respond according to the reversed mapping (e.g., press key *2* for stimulus *A* and key *1* for stimulus *B*). Does this experiment involve one task (with a set of four stimulus–response mappings) or two tasks (defined by color)? When the stimulus changes color across trials, does that constitute a task switch? If so, then is there any evidence of a *switch cost*—a longer response time or higher error rate for color switches compared with color repetitions?

Some insight regarding the answers to these questions has been provided in studies by Dreisbach and colleagues (Dreisbach, Goschke, & Haider, 2006, 2007; Dreisbach & Haider, 2008). They conducted experiments in which word stimuli appeared in different-colored fonts across trials, with each color cuing a specific task (e.g., green cued an animal–nonanimal judgment on the referent of the word and red cued a consonant–vowel judgment on the first letter of the word). The key manipulation was that one group of subjects (the "two-task" group) was informed of the two tasks represented by the color–task mappings, whereas another group of subjects (the "stimulus–response" group) was merely instructed to memorize all the stimulus–response mappings. The main result was a switch cost in performance (associated with color change) for the two-task group but not for the stimulus–response group. Interestingly, when the stimulus–response group was later informed of the color–task mappings, they began to show a switch cost (Dreisbach et al., 2007). Thus, despite subjects experiencing identical trial conditions, their behavior was influenced by whether they were instructed about the existence of different tasks.

Another example of how instructions can influence behavior in task switching situations was provided by Logan and Schneider (2006a). In a previous study of ours (Schneider & Logan, 2005), subjects switched between a parity task (judging whether a digit stimulus was odd or even) and a magnitude task (judging whether a digit stimulus was lower or higher than 5) that were cued by their stimulus categories (i.e., *odd* and *even* were separate cues for the parity task and *Low* and *High* were separate cues for the magnitude task). We observed a cue–target congruency effect such that performance was better when the cue and the target digit were associated with the same category (congruent; e.g., *odd* and *3*) than when they were associated with different categories (incongruent; e.g., *even* and *3*). To investigate the role of instructions in producing this effect, Experiment 2 of our 2006a study involved subjects performing parity and magnitude tasks that were cued by the second or the third letters of the stimulus categories (i.e., *D* for *odd, V* for *even, W* for *low*, and *G* for *high*). We reasoned that this nontransparent mapping between cues and stimulus categories would produce a negligible congruency effect, which is what we observed in the first half of the experiment. However, after subjects were informed of the relationship between the letter cues and the stimulus categories midway through the experiment, there was a substantial congruency effect in the second half. We argued that the new information about the cues altered how they were interpreted, leading subjects to use categorical mediators to guide their behavior.

The findings of Dreisbach and colleagues and of Logan and Schneider (2006a) draw attention to the importance of instructions in task switching situations. As we noted near the end of our 2006a article, the ability to give and to receive instructions is a powerful tool in the human cognitive repertoire, such that "five minutes of verbal instructions can put a human in a state of preparation to perform a task that would take 5 months of training to establish in a monkey" (p. 362). Whether something is considered a task depends on the nature of those verbal instructions, consistent with Logan and Gordon's (2001) definition of a *task* as a propositional representation of instructions for performance. Indeed, the instructions given to subjects in an experiment must define the task(s) at a level that permits comprehension of what has to be accomplished.

In Table 2.1, we offer a definition of a task as a representation of the instructions required to achieve accurate performance of an activity. We also provide a corresponding interpretation in the context of Marr's (1982) theoretical framework for understanding complex information-processing systems. Marr proposed that an information-processing activity can be understood at three levels. The *computational* level addresses the problem to be solved by an information-processing system. The *algorithmic* level addresses the representation of information and the algorithms used to transform that representation (e.g., by translating input into output) to solve the problem. The *implementational* level addresses the physical instantiation of representations and algorithms in information-processing systems such as the brain. We propose that tasks are associated with the computational level in that they are similar to problems that have to be solved. To foreshadow, we associate task sets with the algorithmic level and the neural substrates of task sets with the implementational level (see Table 2.1).

Table 2.1 Definitions of *Task* and *Task Set*

Concept	**Definition**	**Level(s) of Marr's (1982) framework**
Task	Representation of the instructions required to achieve accurate performance of an activity.	Computational: The problem to be solved by an information-processing system.
Task set	Set of representations and processes capable of performing a task, including the parameterization of those processes and the identification of their neural substrates.	Algorithmic and implementational: Representation of information and the algorithms used to transform that representation to solve the problem, including their physical instantiation.

Tasks can also be associated with different time scales of human action. Newell (1990; see also Anderson, 2002) considered a "task" to be an activity that is performed in a span ranging from a few minutes up to several hours, which corresponds to one of his bands of cognition—the Rational Band. The tasks that are typically studied in task switching experiments correspond more closely with his Cognitive Band, where he differentiated between "unit tasks" that take about 10 seconds, "simple operations" that last 1 second, and "deliberate acts" on the order of 100 ms. For example, the parity and magnitude judgments studied by Schneider and Logan (2005) each took about 1 second and would be considered simple operations under Newell's categorization.

Even at the time scale of 1 second, there is some latitude regarding how one defines a task. The flexibility and richness of language allow one to express instructions at many different levels of abstraction, similar to how one can categorize objects (Brown, 1958; Rosch, 1978; Rosch, Mervis, Gray, Johnson, & Boyes-Braem, 1976), classify events (Morris & Murphy, 1990; Rifkin, 1985; Zacks & Tversky, 2001), and identify actions (Vallacher & Wegner, 1985, 1987) at a variety of levels. Figure 2.1 shows different levels at which one can define the tasks used in the studies by Schneider and Logan (2005, 2007a). As mentioned earlier, the 2005 study involved judging whether a digit stimulus was odd or even on some trials or lower or higher than 5 on other trials. These judgments can be considered different tasks—parity and magnitude judgments, respectively—if tasks are defined at the level of stimulus categories (odd and even versus low and high). However, both judgments can also be regarded as versions of the same higher-level task (semantic classification of numbers), although instructions framed at that level would likely be inadequate for accurate task performance. The 2007a study involved judging whether a digit stimulus was lower or higher than 2 on some trials or lower or higher than 7 on other trials. Both judgments can be considered the same magnitude task at the level of stimulus categories (low and high). However, they can also be regarded as different lower-level tasks—relative judgments involving either 2 or 7 as reference points (see also Schneider & Verbruggen, 2008). From extreme perspectives, the tasks in both studies could also be given the high-level task label of doing a psychology experiment or the low-level task label of making keypress responses to stimuli (see Figure 2.1), with the latter corresponding to the level of task definition used for the stimulus–response group in the studies by Dreisbach and colleagues. Thus, tasks can be defined at multiple levels, with the level of abstraction varying with one's perspective. A similar point was made by Morris and Murphy (1990) in the context of event classification:

> Events often do not have ready-made names for them, as objects do. When someone asks you what you are doing, there is often no single name that is the conventional label for that activity. One might easily respond with a number of names that focus on different aspects of the activity, at different levels of abstraction and including more or fewer actions (p. 417).

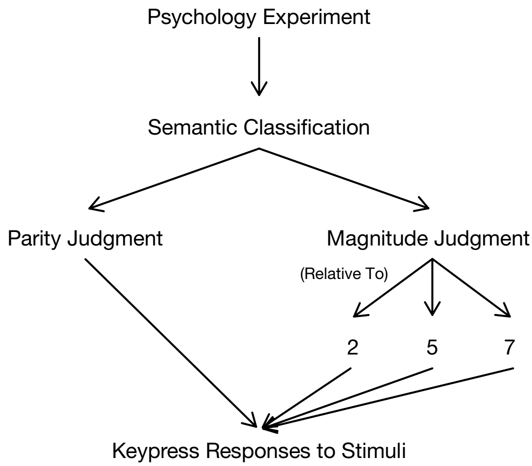

Figure 2.1 Examples of different levels at which tasks can be defined in a typical task switching experiment.

Although there is flexibility when it comes to labeling something as a task, such flexibility does not necessarily portend uncertainty in task definition. In principle, a task can be defined at different levels of abstraction (see Figure 2.1), but in practice, there may be a single level that is prepotent in the minds of most subjects (and researchers). The level at which a task is defined for practical purposes is likely constrained by a number of considerations, three of which we discuss here.

First, there may be a consensus as to what represents a task in an experimental situation. In many studies, relatively good agreement in level of classification has been found among subjects who were instructed to name event-based stories (Morris & Murphy, 1990), identify scenes comprising scripts (Bower, Black, & Turner, 1979), list daily events (Rosch, 1978), or identify breakpoints in filmed event sequences (Newtson & Engquist, 1976; see also Baird & Baldwin, 2001). Tasks may be defined the same way by most subjects in an experiment. Furthermore, there seems to be an implicit consensus among researchers regarding the identities of tasks in many task switching experiments. For example, to our knowledge, nobody has argued that magnitude and parity judgments are the same task. Later in this chapter we argue that both tasks can be performed with the same task set, but that is a different proposition that can be appreciated only if one makes a clear distinction between tasks and task sets.

Second, there may be a *basic level* at which tasks are defined across a range of experimental situations, mirroring the basic levels that have been found or suggested for objects (Rosch, 1978; Rosch et al., 1976), events (Morris & Murphy, 1990; Rifkin, 1985), and scripts (Abbott, Black, & Smith, 1985). The basic level is the level of abstraction at which different entities (e.g., objects, events, or tasks) tend to be categorized. For example, an object may be categorized as a chair at the basic level but as furniture at a superordinate level or as a kitchen chair at a subordinate level (Rosch et al., 1976). The basic level represents a compromise between distinctiveness and informativeness (Morris & Murphy, 1990), providing maximal cue validity while at the same time minimizing cognitive load (Rosch, 1978; Rosch et al., 1976). The net result is that the basic level may be "the most useful level of categorization" (Rosch et al., 1976, p. 435) and, as such, the level that is typically used to categorize items (Brown, 1958) or to make inferences (Abbott et al., 1985). A basic level for tasks has yet to be explicitly identified, but it would likely map onto the same level at which subjects and researchers mutually distinguish between different tasks, as discussed earlier. For example, magnitude and parity judgments may correspond to a basic level of task definition.

Third, there may be a constraint on the highest level at which a task can be defined. As mentioned earlier, what constitutes a task is often determined by instructions. For subjects to respond appropriately in an experiment, they must receive instructions that contain the minimum amount of information required to enable accurate task performance. If a task is defined too abstractly, then subjects may be unable to identify many of the task's attributes (Morris & Murphy, 1990; Rifkin, 1985; Rosch et al., 1976) and, as a result, they may be unable to achieve the desired balance between distinctiveness and informativeness (Morris & Murphy, 1990). For example, if subjects are instructed to perform "semantic classification" of numbers but they are not informed of the relevant semantic attributes (e.g., parity and magnitude), then they will likely be unable to perform the task accurately in the absence of feedback. A clear conception of the experiment can be achieved only if tasks are defined at a lower level that provides sufficient information (e.g., the relevant stimulus categories) for performance. Thus, one could argue that there is an upper-level informational constraint on the hierarchy used to define tasks.

Despite these constraints on task definition, it can be difficult to firmly establish what the tasks are in an experiment. Instructions may be expressed in different ways that convey all the relevant information but produce divergent effects on behavior, as seen in the work of Dreisbach and colleagues and of Logan and Schneider (2006a). In the context of writing or reading instructions, there may not be a consensus among researchers or subjects on whether a given experiment involves one or two or more tasks. Similarly, researchers or subjects may not agree on a basic level for defining tasks in a specific domain.

However, uncertainty about task definition need not be a crippling problem for task switching research. Indeed, the ever-growing body of literature on task switching—in the absence of clear *task* definitions—indicates that the field has not been hindered. Regardless of whether one considers an experiment to have one or two tasks, it is generally the case that one can establish what constitutes accurate task performance. That is, most experiments involve clearly defined mappings of stimuli to responses, enabling the researcher to determine whether subjects are following instructions and performing the task(s) as designed. From this perspective, the critical element is not how a task is defined but rather how it is performed. In the context of Marr's (1982) levels of analysis, the problem specified at the computational level may not be as important as how it is solved at the algorithmic level. In the domain of task switching, the algorithmic level—which indicates how a task is performed—is represented by the task set.

WHAT IS A TASK SET?

> "What constitutes a task set is seldom explained, the differences between task sets are rarely identified, and the distinction between tasks and task sets is hardly ever discussed."
>
> —Schneider and Logan *(2007a, p. 118)*

Despite its prevalence as a theoretical construct, precise definitions of task set are as rare today as they were in the past (see Dashiell, 1940; Gibson, 1941). In task switching research, a *task set* has been loosely defined as a set of internal control settings, a state of preparation, a collection of stimulus–response or category–response mapping rules, or a configuration of perceptual, cognitive, and motor processes that enables achievement of a task goal, especially in the context of competing goals and other sources of interference (e.g., Allport, Styles, & Hsieh, 1994; Mayr & Keele, 2000; Rogers & Monsell, 1995). We say "loosely defined" because there is no agreed-upon definition of task set and most of the definitions themselves are ill-defined. For example, what is a "set of internal control settings?" What is it about one set of internal control settings that makes it different from another? What changes are made to internal control settings to accomplish "task-set reconfiguration" (e.g., Monsell & Mizon, 2006)? These questions highlight some of the ambiguity that one finds with verbal theorizing in the domain of task switching.

We think this ambiguity can be avoided and task sets can be placed on firmer ground by defining them in the context of computational models. A computational model is a formal specification of the representations and the processes needed to perform a task. In other words, it instantiates a task set in precise terms that can be realized by computer simulation or expressed as mathematical equations (which might characterize processes that could also be simulated). Computational models help one avoid some of the pitfalls associated with verbal theorizing, such as ambiguities in the mapping of words to meanings and the treatment of labels as explanations (Hintzman, 1991). In so doing, they can improve reasoning about the aspects of cognition represented in the model and facilitate shared understanding of ideas between researchers (Farrell & Lewandowsky, 2010). Computational models also have the advantages of generating quantitative predictions that can be compared with behavioral data (e.g., response time and error rate) and potentially revealing nonintuitive, complex interactions among different processes.

Fortunately, several computational models of task switching have been developed in recent years (e.g., Altmann & Gray, 2008; Brown, Reynolds, & Braver, 2007; Meiran, Kessler, & Adi-Japha, 2008; Schneider & Logan, 2005; Sohn & Anderson, 2001). The models differ in many ways, ranging from their assumptions to their scope of application, and are even instantiated in different types of modeling frameworks (e.g., mathematical model—Schneider & Logan, 2005; neural network—Brown et al., 2007; production system—Sohn & Anderson,