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.

Schneider, D. W., & Logan, G. D. (2014). Tasks, task sets, and the mapping between them. In J. A. Grange & G. Houghton (Eds.), *Task switching and cognitive control* (pp. 27–44). New York: Oxford University Press.

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).

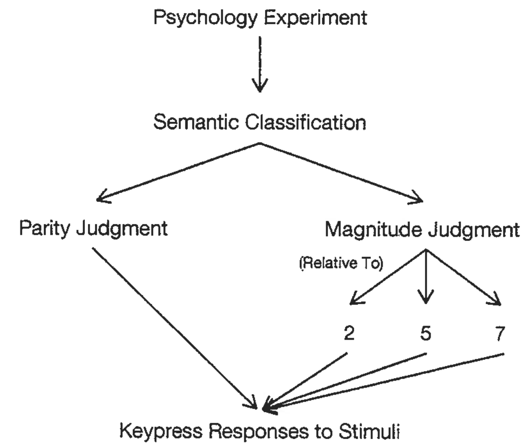

Figure 2.1 Examples of different levels at which tasks can be defined in a typical task switching experiment.

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, 2001). Despite these differences, all the models define task sets at a level of detail sufficient to perform the tasks of interest. Consistent with this view, Logan and Schneider (2010) defined a *task set* as a "set of parameters in a computational model that is sufficient to program the model to perform particular task-relevant computations" (p. 416). In Table 2.1, we offer a broader definition of a *task set* as a set of representations and processes capable of performing a task, including the parameterization of those processes and the identification of their neural substrates.

For example, consider the model of task switching developed by Schneider and Logan (2005), which is a member of a broader class of models subsumed under the Executive Control Theory of Visual Attention (ECTVA; Logan & Gordon, 2001) and the Instance Theory of Attention and Memory (ITAM; Logan, 2002; see also Logan, 2004). The model assumes that task switching performance reflects two key processes: cue encoding and compound cue retrieval. Cue encoding is the process by which a semantic, categorical representation of a task cue is formed (Arrington, Logan, & Schneider, 2007; Logan & Bundesen, 2003; Schneider & Logan, 2005). Priming of cue encoding by repetition or association has been shown to be at least partly responsible for observed switch costs in cued task switching performance (e.g., Logan & Bundesen, 2003; Logan & Schneider, 2006b; Schneider & Logan, 2006, 2007b, 2011). The representation of the cue is used in conjunction with a semantic, categorical representation of the target stimulus (Schneider & Logan, 2010) to select a response. Compound cue retrieval is the process by which information from the cue and the target is combined to probe memory for evidence in favor of one response or another (Logan & Schneider, 2010; Schneider & Logan, 2005, 2009a). The way in which conflicting information from the cue and the target affects compound cue retrieval has been shown to account for several congruency effects seen in task switching performance (e.g., Schneider & Logan, 2005, 2009a).

In the context of Schneider and Logan's (2005) model, a task set is a set of internal control settings but it is one that is clearly defined in terms of various model parameters. For example, two important parameters in compound cue retrieval are the bias and the criterion. The bias parameter controls the strength of the bias toward a specific response category, such that increasing the bias for a response category makes the model more likely to select that response. The criterion parameter controls how much evidence is needed for one response category over the other before termination of the decision process for response selection (modeled as a random walk; see Ratcliff, 2001). Increasing the criterion makes the model select a response more slowly but also more accurately, thereby allowing it to trade speed for accuracy. Changing either the bias or the criterion qualifies as task-set reconfiguration because those parameters partly define the task set (see Logan & Gordon, 2001). Thus, rather than speculating about task-set reconfiguration in a task switching situation, one can investigate whether and which parameters of the model need to change to accommodate different tasks.

An example of such an investigation was provided by Logan and Schneider (2010). In that study, we focused on modeling the target functions for the magnitude and parity tasks in the data from Schneider and Logan (2005). A target function is a pattern of performance across different target stimuli that presumably reflects differences in how targets are either represented or processed. The target function for the magnitude task revealed that performance improved as the distance of the target from 5 (the reference point for making the magnitude judgment) became longer. This finding corresponds to the well-known *distance effect* in numerical judgments (Moyer & Landauer, 1967; for reviews, see Banks, 1977; Moyer & Dumais, 1978). The target function for the parity task revealed that performance was better overall for even targets than for odd targets, consistent with previous research (Hines, 1990).

The different target functions might be used to infer that the tasks require different task sets (and, by extension, that switching between the tasks requires task-set reconfiguration), but Logan and Schneider (2010) presented modeling results showing that this need not be the case. More specifically, we demonstrated that two versions of our model of compound cue retrieval—of which one involved task-set reconfiguration and one did not—provided equivalent fits to the empirical target functions. The reconfiguration version of the model involved changing the bias parameter to favor the task-relevant categories (e.g., *odd* and *even* when the parity task was relevant), whereas the nonreconfiguration version of the model could accommodate the different target patterns with no change in bias by having the cue representation "gate" the evidence from the target to favor the task-relevant categories. The shapes of the target functions were determined by assumptions about how magnitude and parity are represented in memory (e.g., Dehaene, Bossini, & Giraux, 1993; Miller & Gelman, 1983; Shepard, Kilpatric, & Cunningham, 1975). The bias parameter and the cue representation each allowed the model to emphasize one representation over the other, resulting in the production of different target functions. Thus, we were able to use computational modeling to show that magnitude and parity tasks could be performed with either the same task set or different task sets.

Task sets and their reconfiguration can also be explored in the context of other computational models (e.g., Altmann & Gray, 2008; Brown et al., 2007; Gilbert & Shallice, 2002; Kieras, Meyer, Ballas, & Lauber, 2000; Meiran et al., 2008; Sohn & Anderson, 2001), so researchers do not need to endorse our model or subscribe to a specific modeling framework. Moreover, even though various models may differ at a superficial level, many of them share deeper similarities in their assumptions about how task sets are represented and how task information is processed. Such similarities at the algorithmic level of Marr's (1982) framework may prove useful in understanding how task sets are represented at the implementational level in the brain. That is, research on the neural basis of task sets (e.g., Dosenbach et al., 2006; Miller & Cohen, 2001; Yeung, Nystrom, Aronson, & Cohen, 2006; for an overview, see Schneider & Logan, 2009b) may benefit from a better understanding of the mechanistic basis of task sets, and vice versa.

MAPPINGS BETWEEN TASKS AND TASK SETS

Despite the fact that the terms "task" and "task set" are often used interchangeably, the preceding text indicates that they can and should be distinguished (e.g., see Table 2.1). A task is an instruction-based representation of what to do that can be conceptualized at a computational level of analysis. A task set is a delineation of the representations and processes involved in doing a task, often cast in the form of a computational model, which can be conceptualized at algorithmic and implementational levels of analysis. Once this distinction is recognized and appreciated, one can begin to think more critically about the mapping between tasks and task sets in different experimental situations. More specifically, one can abandon the commonplace assumption that there is a one-to-one mapping of tasks to task sets.

The one-to-one mapping assumption is that every task is associated with a unique task set, which implies that task switching always involves task-set reconfiguration. The assumption is prevalent among many formal and informal theories of task switching and is often implicit in how researchers interpret their task switching data. For example, in a task switching experiment involving two nominally different tasks, switch costs are frequently interpreted by default as either direct or indirect evidence that task-set reconfiguration has occurred. Although there are many situations in which the one-to-one mapping assumption is likely valid, we think it is prudent to consider situations in which it may be invalid; that is, situations in which there may be many-to-one or one-to-many mappings of tasks to task sets.

A many-to-one mapping is a case of different tasks being performed with the same task set. For example, consider the tasks of judging whether a famous name is that of a male or a female or that of a musician or an actor. The tasks are associated with distinct semantic attributes—gender and occupation—and they can be labeled as nominally different tasks. However, both tasks can be performed by memory retrieval, using the name to probe a vast store of semantic knowledge in memory about famous people. If the tasks were to be modeled with compound cue retrieval (Schneider & Logan, 2005, 2009a), then the target name would access several different semantic attributes in memory and the task cue would constrain retrieval of those attributes to the one that is most relevant. This retrieval mechanism would function in the same way regardless of the task, providing an example of how two tasks can be accomplished with a single task set.

We made a similar argument in previous work involving tasks such as magnitude and parity judgments (e.g., Schneider & Logan, 2005). We argued that magnitude and parity information could be retrieved from memory using a common task set, and we presented a "proof of concept" by showing that it could be done in the context of a computational model that provided satisfactory fits to empirical data. This led us to give our 2005 article the provocative title "Modeling Task Switching Without Switching Tasks," but a more appropriate title would have been "Modeling Task Switching Without Switching *Task Sets*." Thus, even we are guilty of conflating tasks and task sets in the past.

Many-to-one mappings of tasks to task sets are not restricted to task switching situations; they can also be found in other domains of cognitive psychology. For example, analogical problem solving is based on the idea that it may be possible to use the solution to one problem to solve another problem (i.e., there is a many-to-one mapping of problems to solutions), even if the problems differ in their surface features. In a classic study, Gick and Holyoak (1980) explored analogical transfer from a military story about attacking a fortress to a medical story about using radiation to destroy a tumor. A many-to-one mapping arose from the fact that the dispersion solution to the fortress problem (e.g., divide the army into small groups that converge simultaneously on the fortress from multiple roads) could be applied to the tumor problem (e.g., use low-intensity rays that are directed simultaneously toward the tumor from multiple angles), demonstrating that a relatively abstract task set was not restricted to a single situation. The instantiation of a many-to-one mapping in analogical problem solving may depend on being able to map the relational structure of one problem to that of another (Gentner, 1983) or being reminded of the applicability of a previous solution to a current problem (Ross, 1984), but the overarching point is that such mappings exist.

A one-to-many mapping is a case of the same task being performed with different task sets. For example, consider the task of judging whether a number is odd or even. At least two different task sets could be developed to perform this parity judgment. One task set could be based on an algorithm that involves dividing the number by 2 and checking to see whether there is a remainder. An alternative task set could involve engaging in direct memory retrieval, drawing on the knowledge that any number with a 0, 2, 4, 6, or 8 in the units position is an even number. These distinct mechanisms for determining parity provide an example of how a single task can be accomplished with different task sets.

However, the mechanisms underlying the task sets for performing the task do not necessarily have to be different. Two task sets could be based on the same mechanism but involve different parameterizations of it. Recall that *task sets* are defined as sets of parameters in the family of models of which our task switching model is a member (e.g., ECTVA; Logan & Gordon, 2001; ITAM, Logan, 2002). We mentioned two of the parameters in the task set (the bias and the criterion), but there are additional parameters such as a priority parameter that determines the attention weights given to stimuli and a feature-catch parameter that determines the proportion of features that are "caught" in the perceptual organization of the stimulus display (Logan, 1996; Logan & Gordon, 2001). It may be possible for the performance of a given task to be controlled in similar ways by different parameters. For example, Logan and Gordon noted that the bias and the priority parameters operate in the same manner, acting as gain controls on the evidence acquired from stimuli. Thus, there are likely circumstances under which equivalent task performance can be achieved by either modulating the bias parameter while holding the priority parameter constant or modulating the priority parameter while holding the bias parameter constant. Each parameter combination would be considered a different task set that accomplishes the same task.

An example of a proposed one-to-many mapping in the task switching literature was provided in a study by Schneider and Logan (2007a). As mentioned earlier, that 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, and both judgments can be considered the same magnitude task at the level of stimulus categories (low and high). However, we argued that the task required different task sets, with the key parameter being an internal control setting associated with the reference point (2 or 7). Indeed, in unpublished modeling work analogous to the work presented in Logan and Schneider (2010), we found that the target functions in Schneider and Logan's (2007a) data, which took the form of distance effects that changed with the reference point (see also Dehaene, 1989; Holyoak, 1978), could be modeled only by changing the bias parameter in compound cue retrieval. In other words, different task sets were needed to model a magnitude task that involved reference point switching.

One-to-many mappings of tasks to task sets can also be found in other domains of cognitive psychology. For example, some theories of automatization in skill acquisition are based on the idea that the same task can be performed in different ways (e.g., Logan, 1988; Rickard, 1997; see also Anderson, 2007). Consider the task of alphabet arithmetic (Logan & Klapp, 1991), which involves verifying equations of the form $M + 3 = Q$ (determining whether Q is three letters down the alphabet from M). Novice subjects typically perform alphabet arithmetic using a counting algorithm: Starting at the initial letter (M), they count through the alphabet for a number of steps equal to the digit addend (3) and then compare the true sum (P) with the presented sum (Q) to determine whether the equation is true or false. Subjects could also use a letter–digit translation algorithm, translating letters into digits ($M = 13$) on which standard arithmetic can be performed ($13 + 3 = 16$) and then translating digits back into letters ($16 = P$) for comparison with the presented sum. However, similar to determining a number's parity, alphabet arithmetic can also be performed by memory retrieval. With practice, alphabet arithmetic facts become stored in memory, enabling direct retrieval of correct responses when presented with studied equations. Automatization of tasks such as alphabet arithmetic has been argued to reflect a transition from an algorithm to direct memory retrieval (Logan, 1988; Rickard, 1997), which is only possible in the context of a one-to-many mapping of tasks to task sets.

It is even possible to have both one-to-many and many-to-one mappings in the same situation. Returning to the domain of problem solving, Luchins (1942; Luchins & Luchins, 1950) conducted experiments in which subjects had to determine how to obtain a specific volume of fluid by pouring fluid into and out of containers of assorted sizes. The same solution method (sequence of operations) could be used for the first few problems (i.e., a many-to-one mapping of problems to solutions), but subsequent problems could each be solved in multiple ways (i.e., a one-to-many mapping of problems to solutions). The question of interest was whether the original solution method was used to solve the later problems that afforded multiple solution methods, with the result being that many subjects persisted in using the original method. Luchins and Luchins (1950) considered the persistent use of the original method to reflect "a special kind of mental set" (p. 279), which is consistent with how we have defined *task set.*

These examples of many-to-one and one-to-many mappings of tasks to task sets challenge the one-to-one mapping assumption implicit in much of the task switching literature. To be clear, the challenge is not that one-to-one mappings do not exist, but that they are not the only possible mappings; therefore, one cannot assume by default that a given situation involves a one-to-one mapping and, by extension, that task switching always involves task-set reconfiguration. However, if one cannot assume that the data from a task switching experiment directly or indirectly reflect task-set reconfiguration, then how can the task switching paradigm be used as a tool for understanding cognitive control?

THE WAY FORWARD

We believe that task switching can serve as a useful paradigm for studying cognitive control if researchers are cognizant of what a task is at the computational level of analysis (e.g., how tasks are defined by instructions), but they focus on how task sets are realized at both the algorithmic and the implementational levels (see Table 2.1). Instead of speculating about whether a given situation involves one or two or more tasks, it may be more fruitful to investigate how the performance of the task(s) can be accomplished by a computational model and how that model might be physically instantiated in the brain.

Despite recent progress, we contend that there is much to be gained from continued development and testing of computational models of task switching. A task set can be explicitly defined in such models (e.g., as a set of parameters) and task-set reconfiguration can be made concrete (e.g., as a change in parameters). If a model requires different task sets to accommodate the data from different tasks, then one is on firmer ground for arguing that the data reflect cognitive control due to task-set reconfiguration. Moreover, given that the nature of the reconfiguration can be specified (e.g., changing a bias or an attention weight in the model), one can make inferences about the nature of the cognitive control process (e.g., response biasing or attention shifting). A researcher would then be in a better position to proceed to the implementational level and investigate whether the hypothesized cognitive control processes involved in task-set reconfiguration depend on the same neural substrates that have been identified for those control processes using other paradigms (e.g., through meta-analyses of neuroimaging results; Buchsbaum, Greer, Chang, & Berman, 2005; Lenartowicz, Kalar, Congdon, & Poldrack, 2010; Wager, Jonides, & Reading, 2004).

An overarching consideration that may serve to guide future research is the recognition that cognitive control in task switching is the outcome or end-product of processing that may or may not involve task-set reconfiguration. That is, cognitive control may be achieved by means of task-set reconfiguration, but it need not be. We discussed this point earlier in relation to our model of task switching and its compound cue retrieval mechanism for response selection (e.g., Logan & Schneider, 2010; Schneider & Logan, 2005, 2009a). The model can accurately perform nominally different tasks without engaging in task-set reconfiguration because it uses the combination of cue and target information to control what is retrieved from memory, with the cue serving a gating function by favoring task-relevant target categories. The outcome of this "information gating" can be interpreted as cognitive control, even though it does not involve task-set reconfiguration. Thus, cognitive control and task-set reconfiguration are separable entities that can and should be distinguished, perhaps with the aid of computational models. There are many paths to cognitive control and task-set reconfiguration is just one of them. We think further progress in research on task switching and cognitive control may come from traveling "off the beaten path" and exploring alternative possibilities regarding how the human mind is able to control itself.

REFERENCES

Abbott, V., Black, J. B., & Smith, E. E. (1985). The representation of scripts in memory. *Journal of Memory and Language, 24*, 179–199.

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

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

Anderson, J. R. (2002). Spanning seven orders of magnitude: A challenge for cognitive modeling. *Cognitive Science, 26*, 85–112.

Anderson, J. R. (2007). *How can the human mind occur in the physical universe?* New York, NY: Oxford University Press.

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.

Baird, J. A., & Baldwin, D. A. (2001). Making sense of human behavior: Action parsing and intentional inference. In B. F. Malle, L. J. Moses, & D. A. Baldwin (Eds.), *Intentions and intentionality: Foundations of social cognition* (pp. 193–206). Cambridge, MA: MIT Press.

Banks, W. P. (1977). Encoding and processing of symbolic information in comparative judgments. In G. H. Bower (Ed.), *The psychology of learning and motivation* (Vol. 11, pp. 101–159). New York, NY: Academic Press.

Bower, G. H., Black, J. B., & Turner, T. J. (1979). Scripts in memory for text. *Cognitive Psychology, 11*, 177–220.

Brown, J. W., Reynolds, J. R., & Braver, T. S. (2007). A computational model of fractionated conflict-control mechanisms in task-switching. *Cognitive Psychology, 55*, 37–85.

Brown, R. (1958). How shall a thing be called? *Psychological Review, 65*, 14–21.

Buchsbaum, B. R., Greer, S., Chang, W.-L., & Berman, K. F. (2005). Meta-analysis of neuroimaging studies of the Wisconsin card-sorting task and component processes. *Human Brain Mapping, 25*, 35–45.

Dashiell, J. F. (1940). A neglected fourth dimension to psychological research. *Psychological Review, 47*, 289–305.

Dehaene, S. (1989). The psychophysics of numerical comparison: A reexamination of apparently incompatible data. *Perception & Psychophysics, 45*, 557–566.

Dehaene, S., Bossini, S., & Giraux, P. (1993). The mental representation of parity and number magnitude. *Journal of Experimental Psychology: General, 122*, 371–396.

Dosenbach, N. U. F., Visscher, K. M., Palmer, E. D., Miezin, F. M., Wenger, K. K., Kang, H. C., ... Petersen, S. E. (2006). A core system for the implementation of task sets. *Neuron, 50*, 799–812.

Dreisbach, G., Goschke, T., & Haider, H. (2006). Implicit task sets in task switching? *Journal of Experimental Psychology: Learning, Memory, and Cognition, 32*, 1221–1233.

Dreisbach, G., Goschke, T., & Haider, H. (2007). The role of task rules and stimulus–response mappings in the task switching paradigm. *Psychological Research, 71*, 383–392.

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

Farrell, S., & Lewandowsky, S. (2010). Computational models as aids to better reasoning in psychology. *Current Directions in Psychological Science, 19*, 329–335.

Gentner, D. (1983). Structure-mapping: A theoretical framework for analogy. *Cognitive Science, 7*, 155–170.

Gibson, J. J. (1941). A critical review of the concept of set in contemporary experimental psychology. *Psychological Bulletin, 38*, 781–817.

Gick, M. L., & Holyoak, K. J. (1980). Analogical problem solving. *Cognitive Psychology, 12*, 306–355.

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

Hines, T. M. (1990). An odd effect: Lengthened reaction times for judgments about odd digits. *Memory & Cognition, 18*, 40–46.

Hintzman, D. L. (1991). Why are formal models useful in psychology? In W. E. Hockley & S. Lewandowsky (Eds.), *Relating theory and data: Essays on human memory in honor of Bennet B. Murdock* (pp. 39–56). Hillsdale, NJ: Erlbaum.

Holyoak, K. J. (1978). Comparative judgments with numerical reference points. *Cognitive Psychology, 10*, 203–243.

Kieras, D. E., Meyer, D. E., Ballas, J. A., & Lauber, E. J. (2000). Modern computational perspectives on executive mental processes and cognitive control: Where to from here? In S. Monsell & J. Driver (Eds.), *Control of cognitive processes: Attention and performance XVIII* (pp. 681–712). Cambridge, MA: MIT Press.

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

Lenartowicz, A., Kalar, D. J., Congdon, E., & Poldrack, R. A. (2010). Towards an ontology of cognitive control. *Topics in Cognitive Science, 2*, 678–692.

Logan, G. D. (1988). Toward an instance theory of automatization. *Psychological Review, 95*, 492–527.

Logan, G. D. (1996). The CODE theory of visual attention: An integration of space-based and object-based attention. *Psychological Review, 103*, 603–649.

Logan, G. D. (2002). An instance theory of attention and memory. *Psychological Review, 109*, 376–400.

Logan, G. D. (2004). Cumulative progress in formal theories of attention. *Annual Review of Psychology, 55*, 207–234.

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

Logan, G. D., & Klapp, S. T. (1991). Automatizing alphabet arithmetic: I. Is extended practice necessary to produce automaticity? *Journal of Experimental Psychology: Learning, Memory, and Cognition, 17*, 179–195.

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.

Luchins, A. S. (1942). Mechanization in problem solving. *Psychological Monographs, 54* (entire issue 248).

Luchins, A. S., & Luchins, E. H. (1950). New experimental attempts at preventing mechanization in problem solving. *Journal of General Psychology, 42*, 279–297.

Marr, D. (1982). *Vision*. New York, NY: W. H. Freeman.

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

Meiran, N., Kessler, Y., & Adi-Japha, E. (2008). Control by Action Representation and Input Selection (CARIS): A theoretical framework for task switching. *Psychological Research, 72*, 473–500.

Miller, E. K., & Cohen, J. D. (2001). An integrative theory of prefrontal cortex function. *Annual Review of Neuroscience, 24*, 167–202.

Miller, K., & Gelman, R. (1983). The child's representation of number: A multidimensional scaling analysis. *Child Development, 54*, 1470–1479.

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

Morris, M. W., & Murphy, G. L. (1990). Converging operations on a basic level in event taxonomies. *Memory & Cognition, 18*, 407–418.

Moyer, R. S., & Dumais, S. T. (1978). Mental comparison. In G. H. Bower (Ed.), *The psychology of learning and motivation* (Vol. 12, pp. 117–155). New York, NY: Academic Press.

Moyer, R. S., & Landauer, T. K. (1967). Time required for judgments of numerical inequality. *Nature, 215*, 1519–1520.

Newell, A. (1990). *Unified theories of cognition*. Cambridge, MA: Harvard University Press.

Newtson, D., & Engquist, G. (1976). The perceptual organization of ongoing behavior. *Journal of Experimental Social Psychology, 12*, 436–450.

Ratcliff, R. (2001). Diffusion and random walk processes. In *International encyclopedia of the social and behavioral sciences* (Vol. 6, pp. 3668–3673). Oxford, UK: Elsevier.

Rickard, T. C. (1997). Bending the power law: A CMPL theory of strategy shifts and the automatization of cognitive skills. *Journal of Experimental Psychology: General, 126*, 288–311.

Rifkin, A. (1985). Evidence for a basic level in event taxonomies. *Memory & Cognition, 13*, 538–556.

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

Rosch, E. (1978). Principles of categorization. In E. Rosch & B. B. Lloyd (Eds.), *Cognition and categorization* (pp. 27–48). Hillsdale, NJ: Erlbaum.

Rosch, E., Mervis, C. B., Gray, W. D., Johnson, D. M., & Boyes-Braem, P. (1976). Basic objects in natural categories. *Cognitive Psychology, 8*, 382–439.

Ross, B. H. (1984). Remindings and their effects in learning a cognitive skill. *Cognitive Psychology, 16*, 371–416.

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. (2006). Priming cue encoding by manipulating transition frequency in explicitly cued task switching. *Psychonomic Bulletin & Review, 13*, 145–151.

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

Schneider, D. W., & Logan, G. D. (2009b). Task switching. In L. R. Squire (Ed.), *Encyclopedia of neuroscience* (Vol. 9, pp. 869–874). Oxford, UK: Academic Press.

Schneider, D. W., & Logan, G. D. (2010). The target of task switching. *Canadian Journal of Experimental Psychology, 64*, 129–133.

Schneider, D. W., & Logan, G. D. (2011). Task-switching performance with 1:1 and 2:1 cue–task mappings: Not so different after all. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 37*, 405–415.

Schneider, D. W., & Verbruggen, F. (2008). Inhibition of irrelevant category–response mappings. *Quarterly Journal of Experimental Psychology, 61*, 1629–1640.

Shepard, R. N., Kilpatric, D. W., & Cunningham, J. P. (1975). The internal representation of numbers. *Cognitive Psychology, 7*, 82–138.

Sohn, M.-H., & Anderson, J. R. (2001). Task preparation and task repetition: Two-component model of task switching. *Journal of Experimental Psychology: General, 130*, 764–778.

Vallacher, R. R., & Wegner, D. M. (1985). *A theory of action identification*. Hillsdale, NJ: Erlbaum.

Vallacher, R. R., & Wegner, D. M. (1987). What do people think they're doing? Action identification and human behavior. *Psychological Review, 94*, 3–15.

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

Wager, T. D., Jonides, J., & Reading, S. (2004). Neuroimaging studies of shifting attention: A meta-analysis. *NeuroImage, 22*, 1679–1693.

Yeung, N., Nystrom, L. E., Aronson, J. A., & Cohen, J. D. (2006). Between-task competition and cognitive control in task switching. *Journal of Neuroscience, 26*, 1429–1438.

Zacks, J. M., & Tversky, B. (2001). Event structure in perception and conception. *Psychological Bulletin, 127*, 3–21.