YOU CAN'T HAVE IT BOTH WAYS:
AN EXAMINATION OF CONGRUENCY EFFECTS IN TASK SWITCHING

by

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Abstract

Environmental contexts help us set relevant goals and guide appropriate behaviors. In situations in which a single stimulus affords multiple responses, cognitive control processes allow us to establish the appropriate goal based on the present context and activate rules associated with the current goal. This enables execution of correct responses, even when those responses are inconsistent with alternative responses afforded by the same stimulus. The experiments in this dissertation use task-switching paradigms to examine how individuals respond to situations in which a single stimulus can afford two responses. These behavioral studies examine congruency effects, the performance differences between congruent trials, for which the same response is always appropriate, and incongruent trials, for which the appropriate response differs depending on the currently-relevant task. Experiments 1 and 2 examine the possibility that congruency effects observed in task switching are fundamentally similar to congruency effects in Stroop paradigms by comparing task-switching congruency effects in conditions with and without Stroop-like interference. In both experiments, congruency effects in task switching interact with Stroop-like congruency effects, suggesting a common mechanism. Based on the results in Experiments 1 and 2, I suggest that automatic activation of a category by attributes of the stimulus that have previously been relevant underlies congruency effects in Stroop and task-switching situations. This hypothesis is supported by findings in Experiments 3 and 4 that task-switching congruency effects are absent for conditions in which a stimulus is never assigned to different categories on different trials. Congruency effects across these paradigms can be accounted for by a generalized model of competition driven by repeated assignment of stimuli to competing categories.

Chapter I

Introduction

In daily life, we often confront challenges when dealing with multiple potential response options. For example, when you hear your cell phone ring, your first instinct might be to press the "talk" button, but there are other possible responses for the phone-ring stimulus. If your cell phone rang while you were listening to a speech, answering the phone would be contextually inappropriate, and you would likely silence the ringer. However, if you noticed that the call was coming from your child's school, you would need to resolve the conflict between two potential responses because each response corresponds to a different goal: during the speech, the appropriate response is silencing your ringer; for the call coming from school, the appropriate response is answering your phone. After a moment, you might resolve this conflict and respond by walking into the hall to answer your phone.

In this dissertation, I interpret a series of experiments that examine the processing that occurs when we are faced with multiple response options. In particular, I am interested in what has been termed the *Task Rule Congruency Effect* (Meiran, 2005), or the increase in errors and reaction time (RT) that occurs when the current stimulus affords different responses according to different goals (phone ringing during speech → silence ringer; number is that of your child's school → answer phone) as compared to when both goals lead to the same response (phone ringing during speech → silence ringer; number is that of a telemarketer → silence ringer). I hypothesize that the mechanisms generating conflict when we must contradict a strong, habitual response (as in Stroop tasks)

are the same as those creating conflict between newly-learned, arbitrary rules in task switching.

In the laboratory, task-switching paradigms provide a method for studying how people deal with competition between multiple response options for a single stimulus. Many researchers have used task-switching paradigms to investigate how cognitive control can be exerted to alternate flexibly between tasks (e.g., Allport, Styles, & Hsieh, 1994; Rogers & Monsell, 1995, Rubenstein, Meyer, & Evans, 2001). Much of this work has focused on exploration of the *switch cost*, the finding that participants are slower and less accurate on trials for which the current task differs from that on the immediately-preceding trial (switch trials) than on trials for which the current task is the same as that on the immediately-preceding trial (nonswitch trials). Allport and colleagues argued that the cost associated with switching from one task to another was the result of task-set inertia, a type of proactive interference characterized by the stimulus-response pairing from the previous trial remaining active and interfering with the newly-appropriate stimulus-response pairing relevant for the current trial (1994). Though Rogers and Monsell (1995) provided evidence that much of the switch cost can be attributed to an endogenous task-set reconfiguration such that control is exerted to switch from one task to another prior to the onset of the stimulus, modern theories ascribe some portion of the switch costs to a carryover of stimulus-response associations from previous trials. This residual switch cost remains after long preparation intervals that allow more than adequate time for task-set reconfiguration (e.g., Sohn et al., 2000). There is evidence that stimulus-response associations may not only persist from the previous trial, but may be reactivated by the stimulus even many trials later (Allport & Wylie, 2000). As I will describe below, the reactivation of past stimulus-response associations from previous trials may play a major role in congruency effects.

Though competition has been evaluated mostly in the context of difficulty switching from one task to another, a potentially relevant, competing task set can impact performance even on nonswitch trials. Participants are

slower and more error-prone on *incongruent* trials in a mixed run, for which the rules associating the current stimulus to responses for each of the two available tasks indicate different responses, than they are on *congruent* trials, for which the rules associated with both tasks indicate the same response (Sudevan & Taylor, 1987). Congruency effects in reaction time seem to be related specifically to competition that occurs after stimulus presentation as the magnitude of the congruency effect does not diminish with longer preparatory intervals. However, congruency effects do interact with residual switch costs, indicating that both occur at the same processing stage. This dissertation examines how stimulus-driven associations influence the size and presence of congruency effects.

Shared mechanisms of competition

Meiran and colleagues (Meiran, 2000a; Meiran and Kessler, 2008) have proposed that longer reaction times on incongruent compared to congruent trials reflect time needed to resolve interference resulting from activated response category codes in long term memory. By this account, category codes exist in long term memory and become activated by preparation to use them and/or primed by their actual use during the first few mixed-run trials. When a stimulus is presented, it triggers the abstract categories associated with the attributes of this stimulus. On congruent trials, both categories lead to the same response, facilitating performance. On incongruent trials, the two activated categories lead to opposing responses, causing competition. Resolution of this competition requires additional time before executing a correct response.

Task-switching procedures are not the only ones in which multiple response categories may be activated and in competition. Stroop procedures provide a classic and powerful demonstration of the effects of congruent vs. incongruent stimulus-response associations in a single-task context (Stroop, 1935; See MacLeod, 1991 for a review). As in switching procedures, each stimulus is associated with multiple response categories held in long-term memory. In the case of Stroop procedures, the associations result from lifetime experience, whereas in task-switching, the associations are arbitrary and

experiment-specific. The explanation for slowed responses on incongruent Stroop trials is similar to that in task-switching. Kane and Engle (2003) argue that reaction time differences between congruent and incongruent Stroop trials are the result of increased time needed to suppress the responses that are automatically triggered by attributes of the presented stimulus.

Despite the apparent parallels between congruency effects in the Stroop task and those in task-switching paradigms, Meiran and Kessler (2008) specifically argue that the congruency effects seen in task switching are fundamentally different from those that occur in Stroop tasks. Their argument for a difference between Stroop and task-switching congruency effects rests on two points. The first point is conceptual: they claim that congruency effects in task-switching procedures are reliant on intermediate category-response mappings between the stimulus and the response (see Figure 1.1.1). These mappings are arbitrary and novel, existing only in the context of the experiment. In contrast, they describe Stroop effects as relying on direct stimulus-response mappings that are overlearned prior to entering the laboratory (see Figure 1.1.2). The second point is empirical: Meiran (2005) found that spatial-compatibility (Simon) effects were additive with task-switching congruency effects, suggesting independence between these effects. In later arguments he equates Simon and Stroop effects to argue that Stroop effects are likewise dissociable from task-switching congruency effects.

1.1.1. Task-switching congruency effect
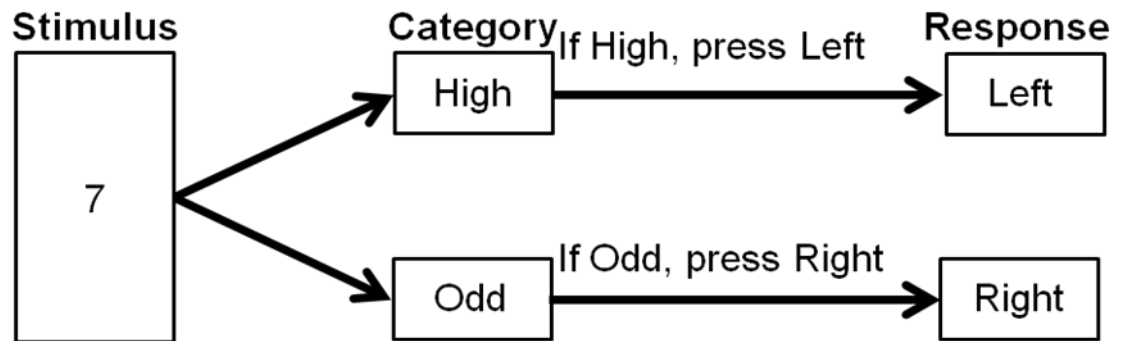
1.1.2. Stroop effect
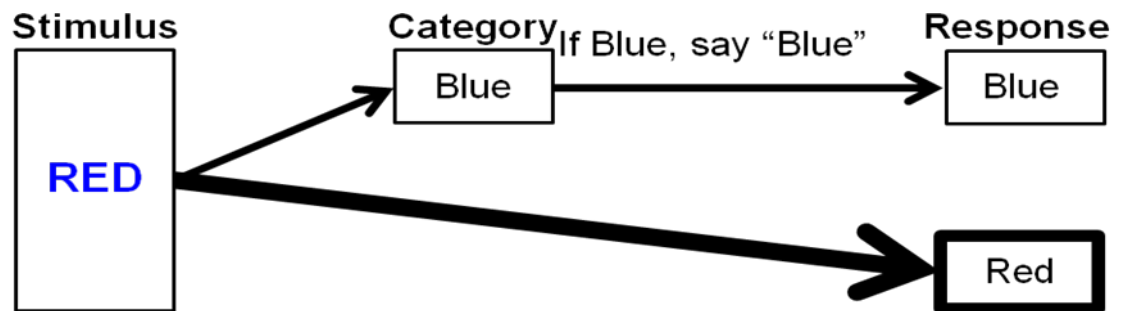
1.1.3. Simon effect
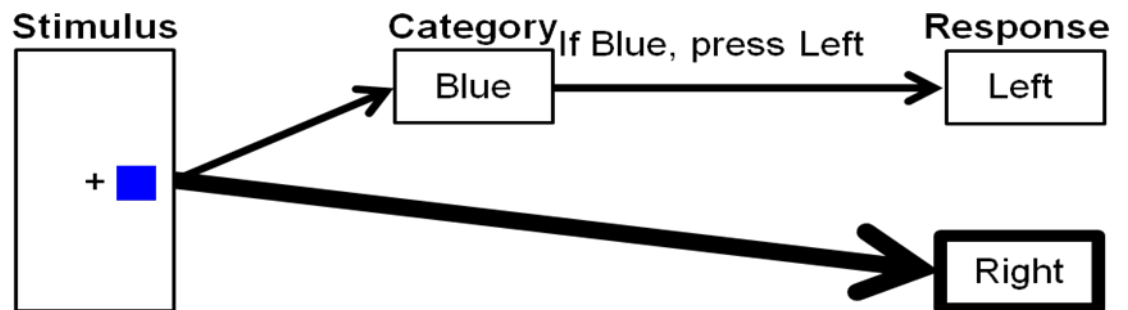
Figure 1.1. Meiran & Kessler model. Panel 1 replicates a figure from Meiran & Kessler (2008) while panels 2 and 3 are drawn based on descriptions of direct stimulus-response mappings. Task-switching congruency effects arise from a mediated pathway in which a stimulus is assigned to a category and each category leads to a response. Stroop and Simon effects arise from a direct stimulus-response mapping for the dominant task. Strong connections are represented by thicker lines and represent highly-practiced associations.

Meiran and Kessler's conceptual argument relates to the learning or automaticity of the associations that connect a stimulus to a particular response, and in particular, whether the connections between the stimulus and response are mediated by a category or are direct. In task-switching procedures, trials are often considered congruent or incongruent based on category-to-response mappings that are novel and experimentally-defined. That is, when presented with the number "7", the assignment of the categories "even" and "higher than 5" to a left key press only exists in the context of the experiment. By contrast, Meiran argues that direct stimulus-response mappings in traditional Stroop tasks are overlearned prior to entering the laboratory. Seeing the word "red" elicits vocalization of the word automatically, regardless of the context.

However, as described earlier, stimuli in task-switching contexts may also elicit past stimulus-response associations automatically, even when those associations oppose those belonging to the currently-active task (see Monsell, 2003). Therefore, I contend that although the distinction between experimentally-defined and pre-existing mappings may be an important factor in determining the magnitude of congruency effects, these effects in both task-switching and Stroop paradigms are due to simultaneous activation of two categories and subsequent competition between corresponding responses. In task-switching, this competition is experimentally created in the mixed-run context by presenting stimuli whose attributes lead to differential categorization by the two potentially-relevant tasks. Repeated categorization of stimuli based on these attributes leads to automatic activation of the category in response to stimulus presentation. In the traditional color-word Stroop paradigm, competition arises even in the single-task context, because the stimulus automatically activates a category and subsequent response. Responding to the non-dominant ink color attribute requires activating the appropriate response and suppressing the response that follows from automatic activation of the irrelevant category (compare Figure 1.1.2 and Figure 1.2.2). Regardless of the source of the competition, simultaneous activation along these two mediated pathways in the incongruent case creates a need for resolution of competition between the two responses.

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The second major component of Meiran and Kessler's argument for a dissociation between Stroop and task-switching congruency effects is evidence that task-switching congruency effects are additive with Simon effects (Meiran, 2005). This evidence was obtained using a paradigm that required participants to respond to the location of a stimulus presented in one of four spaces in a 2x2 square. Participants responded by indicating where the stimulus appeared, either along a vertical dimension (up or down) or along a horizontal dimension (left or right). The critical manipulation with regards to the separation of task-switching and Simon congruency effects is the stimulus-response mapping. In one condition, the upper-left key indicated "up" and "left" and the lower-right key indicated "down" and "right". A stimulus that appeared in the lower-left quadrant would thus be incongruent, and incongruency would be confounded with spatial stimulus-response incompatibility. In the other condition, the response-mapping was reversed, so that the upper-left key indicated "down" and "right." This condition resulted in spatial stimulus-response incompatibility on all trials. Critically, the size of the task-switching congruency effect (e.g., the difference between an upper-left stimulus, for which both "up" and "left" were mapped to the same response, and a lower-left stimulus, for which "down" and "left" were mapped to different responses) remained the same regardless of the overall spatial stimulus-response compatibility. On this basis, Meiran argued that task-switching congruency and Simon effects are independent.

Meiran and Kessler (2008) went on to argue that both the Simon effect and the traditional Stroop effect are driven by pre-existing direct stimulus-response mappings (see Figure 1.1.2). However, as there are fundamental differences between Stroop and Simon effects, it may be invalid to build an argument about Stroop based on Simon findings (Lu & Proctor, 1995; Kornblum, 1992). The Simon effect results from difficulty selecting a response opposite to the side of stimulation, consistent with the argument that this effect occurs due to pre-existing, automatic stimulus-response association (Simon & Small, 1969). There is substantial evidence that Stroop effects may involve an intermediate step of encoding a stimulus according to one attribute rather than the other. Even

for the superficially similar spatial Stroop and Simon effects, distinctions have recently been observed in brain response (Liu et al., 2004). Greater activation in inferior parietal cortex, a region involved in biasing processing in favor of the task-relevant attribute, was found for incongruent relative to congruent trials for a spatial Stroop task but not for a Simon task. This suggests that spatial Stroop effects, but not Simon effects, involve competition based on different attributes of the stimulus beyond strict response competition.

I propose that the Stroop effect is more similar to traditional task-switching congruency effects than to the Simon effect. Specifically, the Stroop effect relies on assignment of a stimulus to a semantic category based on some attribute of the stimulus rather than a direct mapping of stimulus to response. In the Simon effect, the irrelevant dimension (location) does not share a semantic category with the relevant dimension (often color; see Figure 1.2). That is, the color of the stimulus ("blue") is completely orthogonal to the location of the stimulus ("left"); incompatibility occurs only between the side of the stimulus and the side of the response effector. In contrast, in Stroop tasks, the irrelevant dimension often makes use of the same semantic categories as the rel evant dimension. A color word can be semantically categorized as "red", "blue," or "green" based on either the relevant (ink color) or the irrelevant (word identity) dimensions. Incompatibility occurs between the two dimensions of the stimulus, at the level of assignment to a semantic category.

1.2.1 Task-switching congruency effect
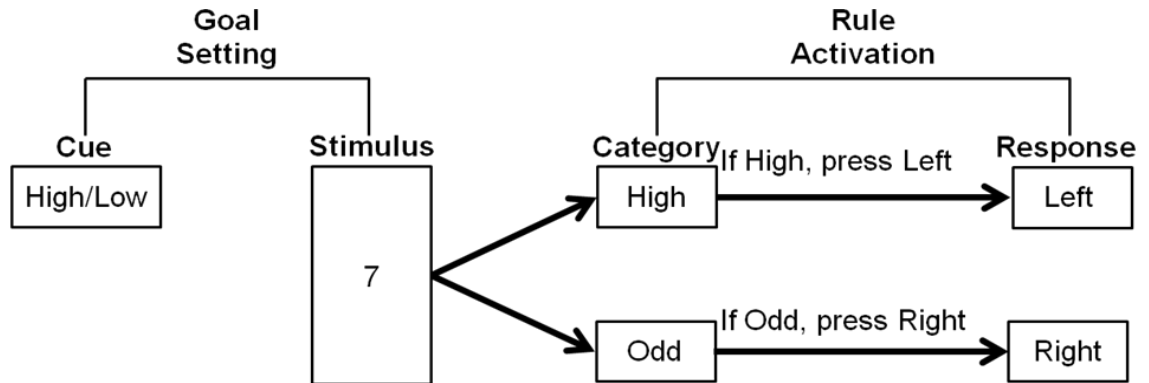
1.2.2 Stroop congruency effect
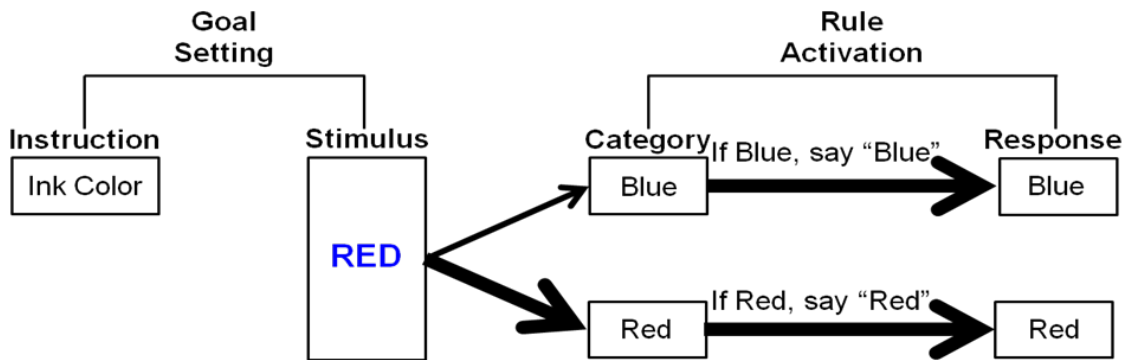
1.2.3 Simon congruency effect
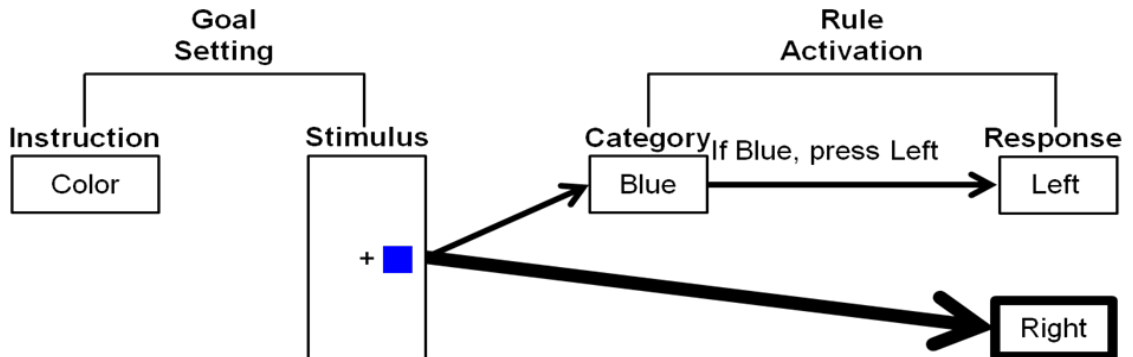
Figure 1.2. Proposed model. Both task-switching and Stroop-like congruency effects arise from a mediated pathway. A stimulus is assigned to a category based on one attribute in accordance with the goal set by the cue. In the incongruent case, the irrelevant stimulus attribute also activates the competing category. Each category is mapped to a response. Strong connections are represented by thicker lines and represent highly-practiced associations.

This distinction is important when thinking about comparisons between congruency effects. Meiran and Kessler (2008) provide excellent evidence that task-switching congruency effects arise from a mediated pathway, in which a given stimulus is assigned to a semantic category before being linked to a response. Specifically, congruency effects occur after training with completely novel stimulus-category associations, but do not exist even after substantial training of stimulus-response mappings if these mappings are direct and do not involve a categorical intermediate. I argue that Stroop effects involve a similar category-mediated pathway and are thus more similar to task-switching congruency effects than to Simon congruency effects.

Figure 1.2 illustrates this idea. In task-switching procedures, the cue indicates which task should be applied to the stimulus on a trial-by-trial basis; this requires goal setting (goal shifting on switch trials or goal maintenance on nonswitch trials). In Stroop procedures, the goal or task remains constant across trials. However, in both cases, the goal is experimentally instructed and indicates which stimulus dimension should be the basis for categorization and subsequent response. The task-irrelevant stimulus dimension automatically activates a category and competes to control the response.

Critically, in both task-switching and Stroop situations, the connections between the stimulus and each potential response are mediated by a semantic category judgment. The competition from the incorrect pathway is typically weaker in task-switching paradigms than in Stroop paradigms because the latter have strong, pre-existing stimulus-to-category mappings. However, the overall structure of the pathways leading to the correct response, and to interference on incongruent trials, is the same for task-switching and Stroop. Both rely on the assignment of a stimulus to a semantic category. This classification mediates the pathway between the stimulus and the response.

In the Simon effect, the task goal again determines the semantic category by which the stimulus should be judged; in this regard, it is similar to the task-switching and Stroop procedures. However, competition arises from a stimulus dimension (location) that is irrelevant to the nominal task and via direct stimulus-

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response mappings. In short, congruency effects in task-switching and Stroop occur because the mappings from the stimulus to both the correct and the incorrect response are mediated by a semantic category judgment. In Simon effects, the correct response is mediated by such a category judgment, but the incorrect, competing response follows a direct stimulus-response mapping without such mediation. The hypothesis that congruency effects in task-switching and Stroop are similar to each other in their reliance on a mediated pathway is the major point of departure between my model and that of Meiran & Kessler.

There is some existing evidence for the idea that Stroop effects are reliant on a mediated pathway. In particular, Stroop color-word congruency effects are smaller but still robust when the response is manual rather than vocal (e.g., Nielsen, 1974). This result contradicts the Meiran model; an entirely direct stimulus-response mapping explanation of Stroop predicts that the effect would require a vocal response. The existence of interference when competition exists between semantic categories in the absence of overlearned category-to-response mappings (e.g., mapping the category Blue to a left response key) is more consistent with a role for abstract category mediators. Conflict at the semantic level has also been demonstrated behaviorally and neurally with Stroop stimuli by contrasting a condition in which the color and word are the same (e.g., "blue" in blue ink) to a condition in which the color and word are different (e.g., "blue" in green ink) but mapped to the same effector for response (e.g., blue and green responses with the left hand, red and yellow responses with the right hand; De Houwer et al, 2003; Van Veen & Carter, 2005). Again, the presence of a level of semantic conflict separate from response conflict indicates a role for category mediators in Stroop-like tasks. De Houwer and colleagues showed that this effect was not likely to originate from a subvocal naming response as results were unchanged under an articulatory suppression condition.

My model also makes explicit connections to previous task-switching models. Specifically, Rubenstein, Meyer, and Evans suggested that executive control may be exerted at two points to facilitate switching tasks. The first point involves *goal shifting*, the process of removing irrelevant goals and

inserting relevant goals into declarative working memory. A goal guides appropriate interpretation of a stimulus (e.g., when you are attending a speech, your goal is to pay attention to the speech. Deciding to prioritize your role as a parent would require updating the current goal to direct your interpretation of the ringing phone – as something requiring a response instead of something to ignore). Goal shifting is thought to be an endogenous process that can occur prior to the onset of the imperative stimulus if a cue indicating the upcoming task has been presented. The second point at which control is exerted is at *rule activation*, the process of enabling the current task's rules and disabling the previous task's rules in procedural working memory. A rule is a representation linking a stimulus to a response in the context of a given task (e.g., a rule might be "If the goal is to pay attention to the speech and the stimulus is your cell phone ringing with an unknown caller, then ignore the call"). The reduction in switch cost seen after long preparation intervals is the result of the ability to complete goal shifting prior to the imperative stimulus. The residual switch cost that exists even after a substantial preparatory interval is a reflection of rule activation. In accordance with this model and with evidence that task-switching congruency effects interact with residual switch costs but not with length of the preparatory interval (e.g., Sudevan & Taylor, 1987; Meiran, 1996, 2000, 2005), I have placed the mediated pathway leading to congruency effects in the rule activation phase.

In this dissertation, I directly compare task-switching congruency effects Stroop-like congruency effects. Stroop-like conditions are those which, like the traditional color-word condition, involve a disparity in automaticity of processing the two possible stimulus attributes. Importantly, in Stroop-like conditions, this automaticity arises from extensive practice encoding a type of stimulus (e.g., a color word) according to one of the two attributes (e.g., word meaning rather than ink color). I focus specifically on addressing the first part of the Meiran and Kessler argument by comparing congruency effects in conditions with novel stimulus-category mappings to those in Stroop-like conditions in which stimulus-to-category mappings are pre-existing and automatic.

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Current Work

I propose that congruency effects in both Stroop-like paradigms and task-switching procedures arise generally from competition due to simultaneous activation of competing categories. In both cases, there is a currently-relevant and a currently-irrelevant attribute of the stimulus, each of which can be categorized to lead to a response. In the task-switching case, the currently-irrelevant attribute actives a corresponding category because it has been relevant on some previous trial. In the Stroop case, the currently-irrelevant stimulus attribute activates a corresponding category because responding based on that attribute has been relevant on so many previous occasions that it has become overlearned and is automatically activated by the presence of any stimulus that affords such categorization.

I propose that RT congruency effects, as a reflection of the need to resolve competition between responses, will vary in magnitude depending on the level to which a category is automatically activated in response to the currently-irrelevant stimulus attribute. I expect congruency effects to be small in situations in which there is little prior experience linking the stimulus to one of the potentially-relevant categories (that is, when stimulus-to-category assignment is novel to the experimental context). I expect these congruency effects to be larger when the currently-irrelevant attribute activates a category more automatically due to recent practice or to overlearning outside of the experimental context.

Prior evidence that guides these hypotheses includes the fact that task-switching congruency effects are smaller in experiments that use stimuli that do not evoke an automatic response than in experiments with Stroop-like stimuli (e.g., Sudevan & Taylor, 1987, Allport et al., 1994, Cepeda et al, 2001). Similarly, congruency-related differences in brain activation tend to be small and unreliable when stimulus-category mappings are relatively novel to the experimental context (Gruber et al., 2009; Brass et al, 2009; Ruge et al., 2009). Congruency effects are large when stimuli are Stroop-like (Aarts et al., 2009; MacDonald et al., 2000). When congruency effects can be found in the absence of overlearning, they include activation differences in anterior cingulate cortex,

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which also shows congruency-related differences with Stroop-like stimuli (Liston et al., 2006; MacDonald et al., 2000).

This dissertation focuses specifically on comparing congruency effects in conditions in which stimulus-to-category associations are novel at the beginning of the experiment to Stroop-like conditions in which overlearning leads to automatic activation of a category when a stimulus is presented. The first experiment compares a task-switching procedure in which stimulus-to-category associations are novel to the experiment to two procedures that use (Stroop-like) stimuli with strong, pre-existing stimulus-category associations. Later experiments rule out potential confounds of stimulus properties and provide evidence that congruency effects that occur in task-switching procedures with experimentally-assigned stimulus-category associations occur after repeated categorization of a set of stimuli; eliminating this repetition can eliminate reaction time congruency effects.

Chapter II

Relationship Between Task-Switching and Stroop-Like Congruency Effects

Objective

Congruency effects in many task-switching paradigms occur once the initial trials of the mixed run prime the categories associated with both tasks. Such effects occur even in the absence of switching behavior if switches are intended or expected (Yehene et. al., 2005). The magnitude of congruency effects in reaction time appears to be increased by extensive task practice (Meiran & Kessler, 2008). Practice may have this effect by strengthening stimulus-category associations. If strengthened stimulus-category associations increase congruency effects, I would expect that conditions in which categorization of one attribute of a stimulus is overlearned and very strong (e.g., in a Stroop-like task) would show larger RT congruency effects than conditions in which stimulus-category associations are arbitrarily introduced in the laboratory. This experiment compares congruency effects in a condition without pre-existing, overlearned associations to those in Stroop-like conditions in which one abstract category is automatically activated by one attribute of the stimulus.

Method

Participants.

Forty-eight undergraduates (19 female; mean age = 19.06, SD = 1.33) participated for partial course credit. All spoke English as their first language or had learned it by age seven.

Stimuli.
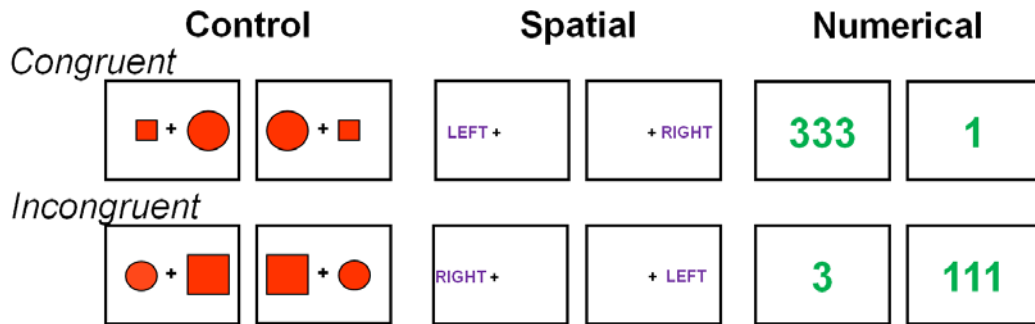
Figure 2.1. Experiment 1 conditions. There were two congruent and two incongruent stimuli repeated randomly throughout each condition. Stimulus color indicated the currently-relevant task.

Figure 2.1 illustrates stimuli for the three conditions: Control, Numerical, and Spatial. For each trial, the current task was indicated by the color of the stimulus. Each task was assigned a unique color. Colors were not recycled across conditions. (1) In the Control condition, participants indicated the position of the larger shape or the position of the circle. (2) In the Spatial condition, participants responded to the meaning of the word or its position on the screen. (3) In the Numerical condition, participants responded to what number they saw or on how many digits they saw. Stroop-like stimulus-category associations exist prior to experimental instruction for both the Numerical and Spatial conditions, but not for the Control condition.

2.2.1 Control
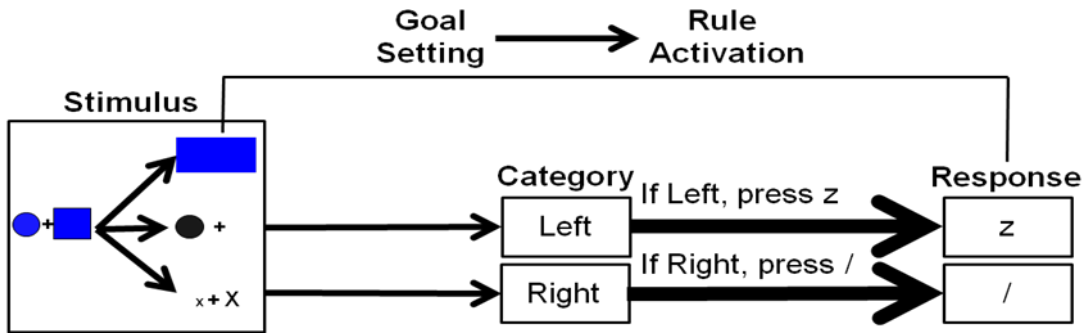
2.2.2 Spatial
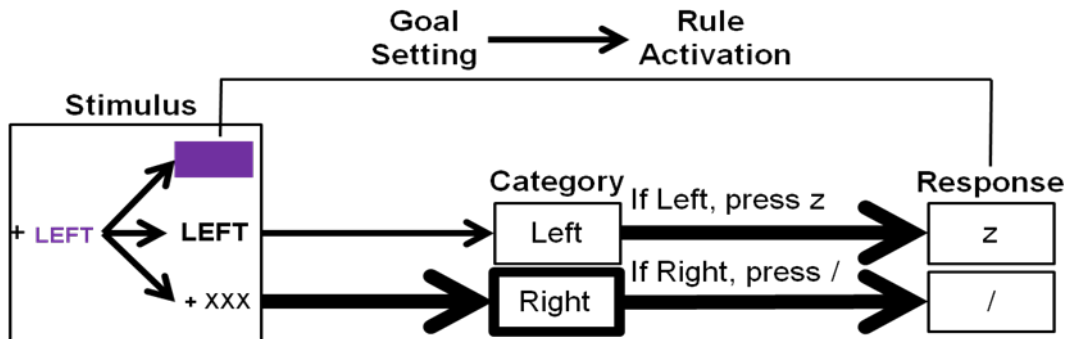
2.2.3 Numerical
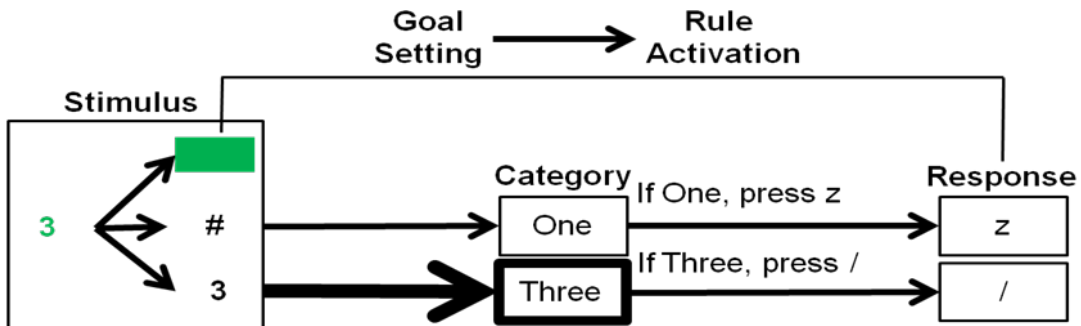
Figure 2.2. Representation of proposed model for each condition in Experiment 1. This model differs from the proposed model in Figure 1.2 as the cue is embedded in the stimulus. Each stimulus is broken into component attributes. Color serves as a cue, allowing for goal setting. One stimulus attribute (e.g., number of digits) allows the stimulus to be assigned to a semantic category according to the current goal. The other stimulus attribute may also lead to the same semantic category (congruent trial) or the opposing category (incongruent trial). Each category is mapped to a behavioral response. Strong connections are represented by thicker lines and represent highly-practiced associations.

Procedure.

For each condition, participants completed six runs of 33 trials each. The first trial of each run was excluded from all analyses. All runs of a condition were completed before moving on to the next condition. Rest periods were available after each run. Trials were self-paced with a 2000 ms upper limit, and were separated from each other by 360 ms of fixation.

The first run for each condition was a pure run: Participants responded to all stimuli based on a single task (task A). The second run was a pure run for the other task (task B). The remaining four runs were "mixed" runs (task A and B intermixed). During mixed runs, half of the trials had the same task as the previous trial (nonswitch) and half had a different task (switch). Task changes were unpredictable and signaled only by a change in stimulus color.

At least four completely self-paced practice trials preceded each pure run. At least eight practice trials preceded the mixed runs. Some participants chose to complete additional practice. Half of the trials in all conditions were congruent and half were incongruent. Condition order and task order within a condition (i.e. which task was identified as task A) were counterbalanced across participants.

Results

In these and all later analyses, reaction times were trimmed to include only accurate trials on which reaction time was greater than 200 ms and less than three standard deviations above the mean for each cell of interest for each participant. Trials immediately following errors were not analyzed for accuracy or response time as switch/nonswitch classification would be uncertain. Huynh-Feldt corrections were applied when the sphericity assumption was violated resulting in non-integer degrees of freedom. Analyses throughout this dissertation focus on reaction time based on previous emphasis in the literature on reaction time as the measure of the interference resolution processes associated with incongruent compared to congruent trials (Kane & Engle, 2003; Meiren & Kessler, 2008). In all experiments presented throughout this dissertation, there was no evidence of a tradeoff between accuracy and reaction

time congruency effects in any condition; correlations between accuracy and reaction time congruency effects were never reliably negative (all p > .4). Correlations between reaction time and accuracy are presented in Appendix A. For completeness, means and statistics for congruency effects in accuracy, log-transformed accuracy, and composite z-scores of reaction time and error rate are presented in Appendices B, C, and D, respectively. Complete reaction time results for Experiment 1 are shown in Table 2.1.

		Congruent			Incongruent		
		Pure	**Nonswitch**	**Switch**	**Pure**	**Nonswitch**	**Switch**
Control	**Shape**	508	689	778	472	673	835
		(73)	(138)	(141)	(74)	(101)	(164)
	Size	438	683	831	413	701	829
		(81)	(163)	(135)	(67)	(134)	(119)
Spatial	**Meaning**	511	695	822	533	786	888
		(67)	(123)	(143)	(66)	(159)	(149)
	Position	364	630	792	382	674	961
		(75)	(150)	(183)	(108)	(177)	(167)
Numerical	**Count**	494	830	972	553	960	1094
		(87)	(157)	(155)	(121)	(149)	(154)
	Identity	462	796	938	465	808	1067
		(63)	(160)	(138)	(72)	(161)	(136)

Table 2.1. Experiment 1 reaction time means and standard deviations for all conditions. Means and corresponding standard deviations are presented in milliseconds.

Spatial and Numerical conditions show Stroop-like properties.

The comparison of congruency effects in task switching with and without the presence of Stroop-like interference pre-supposes that only the Spatial and Numerical conditions show Stroop-like interference. Although in all three conditions, one task was more difficult than the other, only the Spatial and

Numerical conditions showed congruency effects consistent with Stroop interference.

The tests for task difficulty and Stroop interference were conducted on the pure (single-task) trials. On these trials, all conditions showed significantly slower reaction times for one task than for the other (Control: $F(1,47) = 44.95$, $p < .001$; Spatial: $F(1,47) = 134.52$, $p < .001$; Numerical: $F(1,47) = 27.60$, $p < .001$). Reaction times were slower for the shape, meaning, and count tasks. Accuracy effects were consistent with those in reaction time demonstrating a consistent effect of difficulty in each condition (Control: $F(1,47) = 18.26$, $p < .001$; Spatial: $F(1,47) = 14.91$, $p < .001$; Numerical: $F(1,47) = 3.61$, $p = .06$). Though all conditions had a discrepancy between tasks in pure run difficulty, only the Numerical and Spatial conditions showed Stroop-like congruency effects in the single-task runs consistent with overlearning of one task. The Spatial condition showed a main effect of congruency, $F(1,47) = 18.03$, $p < .001$, which was present for both the meaning and position tasks (Task x Congruency effect, $F(1,47) = .30$, $p = .59$) indicating both a Stroop and Reverse Stroop effect. The Numerical condition also showed a main effect of congruency, $F(1,47) = 32.92$, $p < .001$, which was specific to the count task (Task x Congruency effect, $F(1,47) = 33.35$, $p < .001$), indicating a traditional Stroop effect. The Control condition did not show Stroop-like interference. In fact, incongruent trials were significantly faster than congruent trials, $F(1,47) = 57.71$, $p < .001$.

Task-switching and Stroop-like congruency effects are not additive.

The primary question of interest in this experiment was whether the size of the congruency effect in reaction time was smaller in the Control condition (in which stimulus-to-category associations were arbitrarily assigned during the experiment) versus the Numerical and Spatial conditions (in which these associations were overlearned and largely automatic). Analyses comparing congruency effects across conditions focused on trials within the mixed runs. In the pure runs, there was no indication that both tasks were held in mind for the Control condition, making the congruency manipulation moot. Congruency

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effects are consistently larger on switch trials (e.g., Meiran et al., 2005). The Condition x Congruency x Switch interaction was not significant here, $F(2,94) = 1.11$, $p = .33$ due to the fact that the Congruency x Switch interaction was present for all three conditions (Control: $F(1, 47) = 3.91$, $p = .05$; Spatial: $F(1, 47) = 12.95$, $p < .005$; Numerical: $F(1, 47) = 13.47$, $p < .005$). As such, congruency effects were averaged across switch and nonswitch trials. Results supported the hypothesis that overlearned stimulus-category associations led to larger RT congruency effects (Figure 2.3). The Condition X Congruency interaction was significant, $F(2, 94) = 27.85$, $p < .001$.
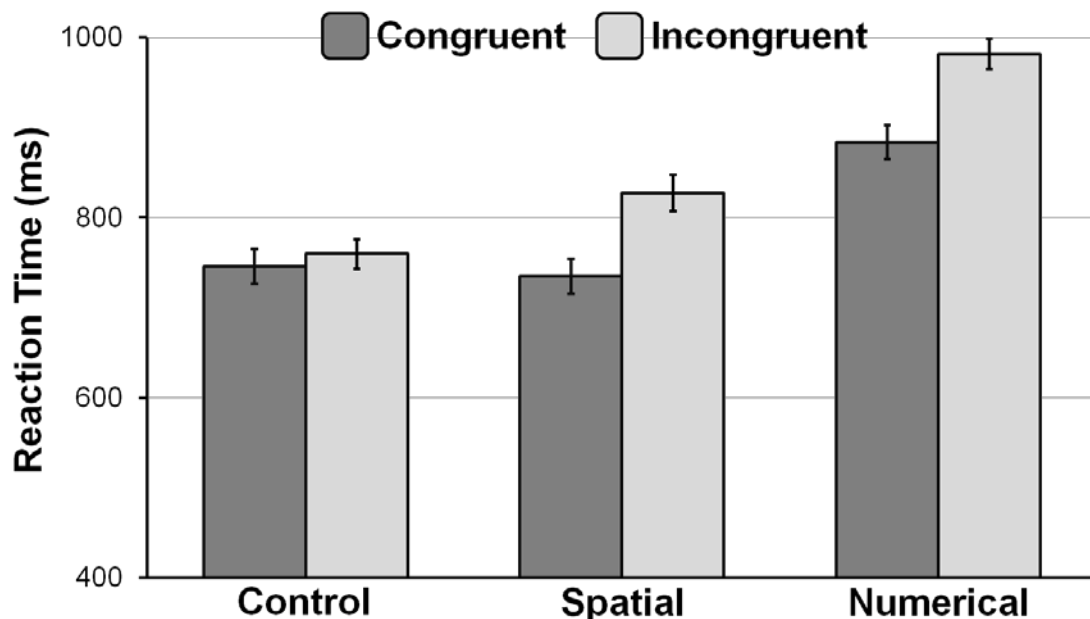
Figure 2.3. Congruency effects are larger in the presence of Stroop-like interference.

Probes of the Condition X Congruency interaction showed a smaller congruency effect for the Control condition than either the Spatial or Numerical condition, $F(1, 47) = 35.41$, $p < .001$ and $F(1, 47) = 48.35$, $p < .001$. These interactions were stable across participants, as 38 out of 48 participants exhibited larger RT congruency effects in the Spatial condition than in the Control condition, and 41 participants displayed larger effects in the Numerical condition than in the Control condition. Since overall reaction time was slower for the

Spatial and Numerical conditions than for the Control condition, it is possible that RT congruency effects were larger for a majority of participants in the Numerical and Spatial conditions due to longer overall reaction time. This was not the case. When congruency effects were considered as a proportion of the overall reaction time for each condition, 37 participants still demonstrated larger congruency effects in the Spatial condition than in the Control condition, and 39 participants showed larger congruency effects in the Numerical condition than in the Control condition.

The Condition x Congruency interactions were significant because congruency effects were present and of similar size in the Spatial condition and the Numerical condition, but not in the Control condition. Congruency effects did not reach significance for the Control condition, $F(1, 47) = 2.69$, $p = .11$. Congruency effects for the Spatial and Numerical conditions were much larger, $F(1, 47) = 88.17$, $p < .001$ and $F(1, 47) = 80.74$, $p < .001$, respectively. The main effects of congruency were stable across participants. While a slight majority of participants (30 out of 48) showed positive congruency effects in the Control condition, positive congruency effects were shown by almost all of the participants in the Spatial and Numerical conditions (45/48 and 46/48 respectively).

Though congruency effects in the Control condition were much smaller than those in the Numerical and Spatial conditions, proportional congruency effects in the Control condition were correlated with those in the Numerical condition, $r(46) = .27$, $p = .07$, almost as highly as congruency effects in the two Stroop-like conditions were correlated with each other, $r(46) = .31$, $p < .05$. This relationship between congruency effects across conditions may indicate the presence of a general interference resolution process supporting response selection when multiple responses are possible for the same stimulus. However, this connection is tenuous as there was no relationship between congruency effects in the Control and Spatial conditions ($p > .8$). The lack of consistent between-condition correlations in congruency effects seen here is similar to the lack of correlation between task-switching congruency effects observed in other

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task-switching paradigms and the lack of reliable correlation observed between congruency effects in different Stroop-like tasks (Yehene & Meiran, 2007; Shilling, Chetwynd, & Rabbitt, 2002; Ward, Roberts, & Phillips, 2001).

Lack of consistent correlation here does not necessarily indicate that there is no commonality in the interference resolution effect. Instead, it may indicate that the congruency effect is driven by the strength of stimulus-to-category associations, which likely differ across subjects depending on their previous experience with a certain set of stimuli and available tasks. There is little reason to expect that this would be consistent across different stimulus sets. For example, a child who is just learning to read may show smaller congruency effects in a traditional Stroop color-word paradigm than an older child who has overlearned word reading. However, there would be no reason to suspect that the younger child would show smaller congruency effects on a color-object Stroop-like paradigm than the older child (e.g., Prevor & Diamond, 2005). In the color-object Stroop, participants must name the picture color rather than naming an object (e.g., say "purple" rather than "carrot" for a picture of a purple carrot), and younger children tend to show larger interference effects than do older children. The congruency effects between color-word and color-object conditions would not be positively correlated because the congruency effect depends on the strength of specific stimulus-category sessions, which differ across conditions.

The presence of similar sized congruency effects in both the Spatial condition and the Numerical condition supports the idea that overlearning of one task rather than other stimulus differences underlie the increase in congruency effects seen in the Stroop-like conditions. This result is consistent with our predictions based on the increased RT congruency effects observed after task practice in a previous session (Meiran and Kessler, 2008).

Differences in the size of congruency effects are not driven by response slowing.

Meiran (2005) has suggested that RT congruency effects may be exaggerated when overall responses are slower. However, it is unlikely that the

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smaller RT congruency effects for the Control condition versus the Numerical and Spatial conditions are related to response slowness. The Condition X Congruency interactions described above remain significant even when the Control condition is only compared to the Spatial condition, which has similar overall RT in the mixed runs (752 vs 781 ms). Additionally, a large majority of participants showed larger congruency effects in the Spatial and Numerical conditions than in the Control condition even when congruency effects were considered as a proportion of overall reaction time in a condition.

To further test the possibility that difficulty drove the differences in RT congruency effects, I divided participants into fast and slow groups (median split) based on their overall mixed RTs for the Control condition. Control mixed-run trials were then analyzed using a Speed (fast, slow) X Congruency (congruent, incongruent) ANOVA. If the previous findings of greater RT congruency effects in the Spatial and Numerical conditions occurred because those conditions were more difficult than the Control condition, RT congruency effects within the Control condition should be greater for slow participants. This was not the case. RT congruency effects did not differ significantly between fast and slow participants, $F(1, 46) = 2.57$, $p = .12$ and, in fact, were numerically smaller for slow participants. (See Figure 2.4.)
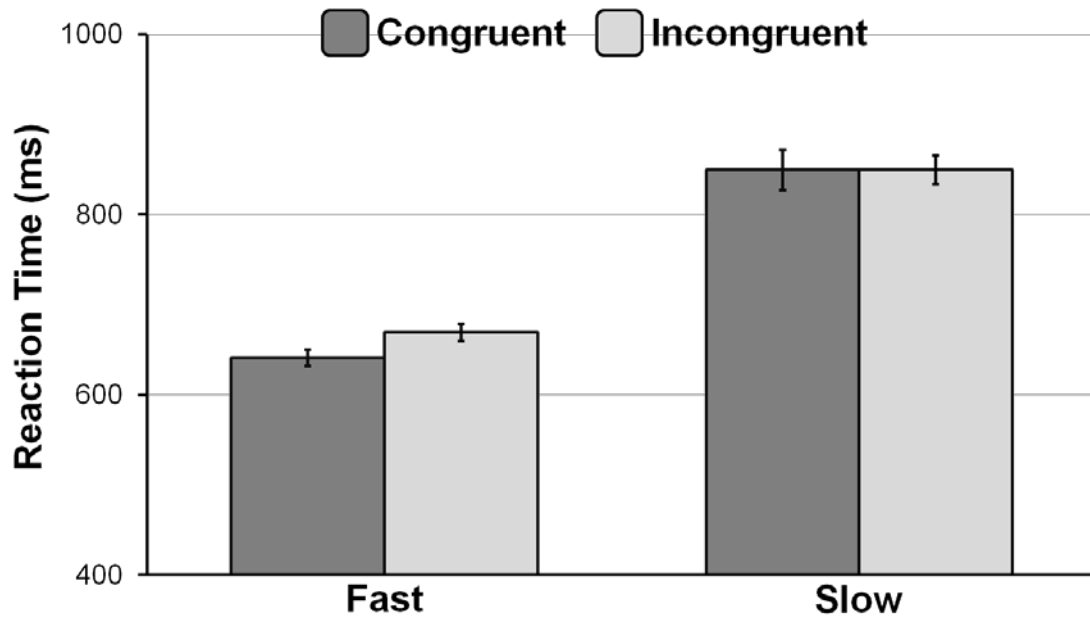
Figure 2.4. Congruency effects in the Control condition do not increase with overall reaction time. When separated by a median split on overall reaction time in the mixed runs, participants with relatively slow reaction times show smaller congruency effects than participants with fast reaction times.

Reaction time congruency effects in the Control condition did not change significantly within the mixed runs.

Though congruency effects were larger in the Spatial and Numerical conditions than in the Control condition, there was a small and nonsigificant trend towards an RT congruency effect in the Control condition. If practice drives the congruency effect, one might expect that this trend occurred due to learning across trials in the mixed runs. This was not the case, as there was no evidence of practice-related increases in congruency effects (see Figure 2.5). Reaction times from the mixed runs were separated into two-run epochs and submitted to a Time (1st half, 2nd half) x Congruency (congruent, incongruent) ANOVA to examine changes in the congruency effect across the mixed runs. Congruency effects in the first two mixed runs did not differ significantly from those in the last two mixed runs, F(1, 47) = 1.66, p = .20, The absence of practice-related increases across a single session is consistent with previous experiments (Meiran and Kessler, 2008). Meiran and Kessler argued that the absence of

practice-related gradual increase in congruency effects in a single session may be due to the fact that the abstract response codes must be consolidated in long-term memory over a night's sleep to create a congruency effect. Though consolidation may contribute to the size of the congruency effect, this reasoning does not explain the non-zero congruency effect in the Control condition. An interesting possibility is that congruency effects may appear after very few instances of assigning a particular stimulus to a category in the context of two available tasks. Such an explanation would be consistent with the existence of priming effects in task-switching after only a single instance of categorizing a stimulus (Waszak et al., 2003). This explanation would also predict that congruency effects might be substantially larger in the mixed runs than in the practice for the mixed run. Unfortunately, in this experiment, there were very few practice trials (eight self-paced trials before the first mixed run).
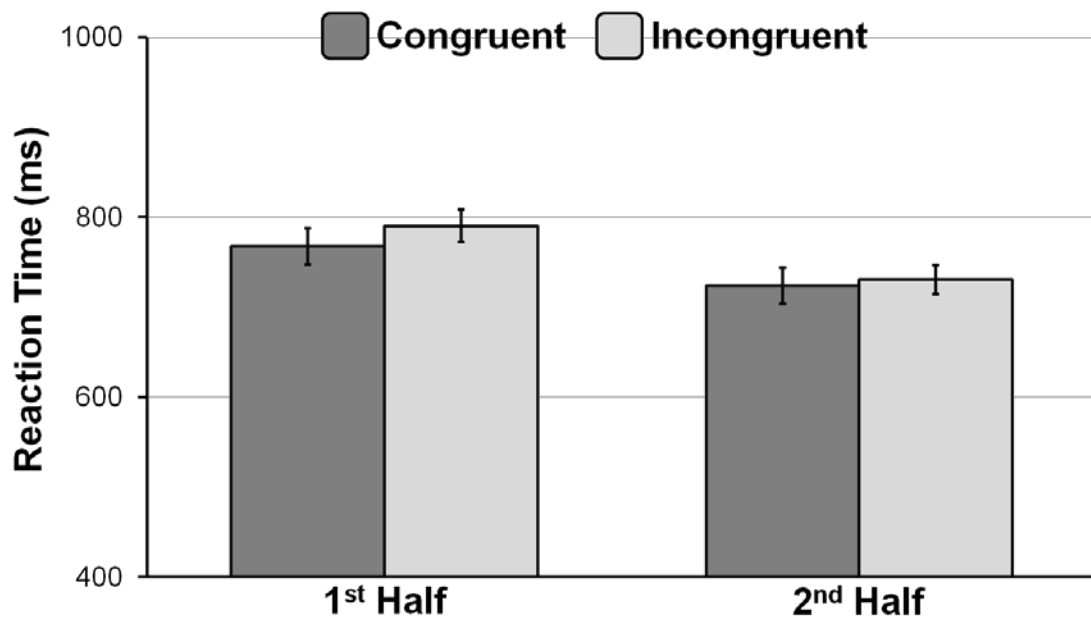
Figure 2.5. Congruency effects in the Control condition do not increase across the mixed runs. The 1st half represents the first two mixed-task runs, while 2nd half represents the last two mixed-task runs for each participant.

Asymmetry in switch costs and congruency effects.

Early research in task switching demonstrated asymmetry in switch costs, such that switch costs were paradoxically larger when switching to the dominant task (e.g., Allport et al., 1994). However, other authors have found a more intuitive pattern, with larger switch costs associated with switching to the more difficult task (e.g., Monsell et al., 2000; Rubenstein et al., 2001). The explanation for the paradoxical asymmetry observed by Allport and others was that the task-set for the dominant task was so strong that substantial inhibition was used to suppress that task-set, making it harder to switch back to that dominant task on a later trial. This argument has been supported by several studies of backward inhibition (e.g., Mayr et al., 2000). Rubenstein and colleagues argued that this pattern is specific to conditions in which the disparity in task difficulty is extremely large, as in Stroop-like conditions, in which stimulus-response rules associated with the dominant task are persistently active in long-term procedural memory. In the present experiment, there was no significant Switch (switch, nonswitch) x Task (shape, size) interaction for the Control condition, $F(1, 47) = .62$, $p = .43$. However, in both Stroop-like conditions, interactions between Switch and Task were significant, Spatial: $F(1, 47) = 43.47$, $p < .001$, Numerical: $F(1, 47) = 5.65$, $p < .05$. In both cases, switching to the dominant task was slower than switching to the nondominant task. These results are consistent with previous work indicating that strong disparities in automaticity between tasks lead to paradoxical switch cost asymmetry.

Given the switch cost asymmetry described above, I examined the Switch x Congruency interaction for differences between tasks (Figure 2.6). If the differences in congruency effects between conditions presented earlier are due specifically to the overlearning of one task in the Stroop-like conditions, congruency effects might be different across tasks. Specifically, if the congruency effect is an indication of competition between responses and is influenced by overlearning of one task, the difference in congruency effects on nonswitch and switch trials should be larger for the dominant task.

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This pattern was demonstrated in the present experiment. The Congruency x Switch x Task interaction was significant for both the Spatial, $F(1, 47) = 38.39$, $p < .001$, and Numerical, $F(1, 47) = 11.24$, $p < .005$, conditions. These interactions exist because the congruency effect was larger on switch than on nonswitch trials only for the dominant task in both conditions. On nonswitch trials of the dominant task, the attribute that automatically activates a category due to overlearning is the same as the currently-relevant attribute according to task instructions and is also the attribute that was primed most recently on the previous trial. This results in quick responses even on incongruent trials. On switch trials to the dominant task, however, the currently-relevant stimulus attribute does not lead to automatic activation of the category because the components of the corresponding task set were strongly inhibited on the previous trial. This inhibition leads to increased response times when the activation of the pathway corresponding to this attribute must be increased above that of the attribute that was primed most recently on the previous trial. The Congruency x Switch x Task interaction was also significant for the Control condition, $F(1, 47) = 21.55$, $p < .001$, but in this case, the congruency effect was larger on switch trials than on nonswitch trials for the more difficult shape task. This pattern is opposite that shown by the Stroop-like conditions in terms of task difficulty.
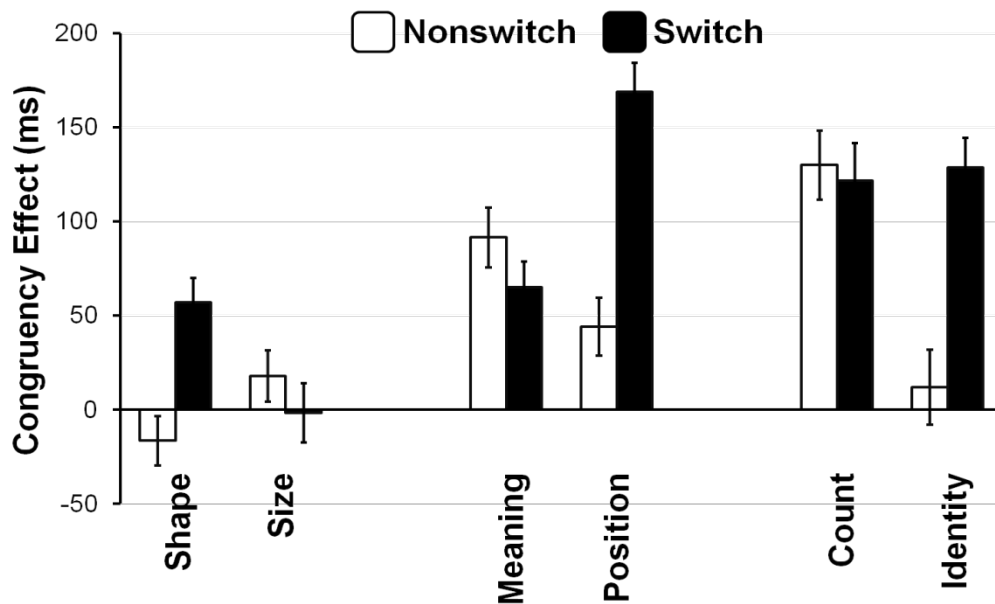
Figure 2.6. Switch difference in congruency effects is larger for the dominant task in Stroop-like conditions. The congruency effect is larger for switch trials than nonswitch trials only for the dominant task in the Spatial and Numerical condition. No such task separation is seen in the Control condition.

Discussion

The present experiment suggests that overlearning of stimulus-category associations increases congruency effects in reaction time, due to automatic activation of the category associated with the dominant stimulus attribute. Both the Spatial and Numerical conditions showed Stroop-like single-task congruency effects, but the Control condition did not. Additionally, the Control condition showed a nonsignificant congruency effect in the mixed runs that was much smaller than the significant congruency effects observed in the Spatial and Numerical conditions. These differential congruency effects seem to be due to overlearning of one task in the Stroop-like conditions, as the effects in the Spatial and Numerical conditions were of similar size. These results stand in stark contrast to those presented by Meiran comparing task-switching congruency effects to Simon effects (2005). Meiran showed that Simon effects were additive with task-switching congruency effects while these results show that Stroop-like

congruency effects are not additive with task-switching congruency effects. While Simon effects are fundamentally different from task-switching congruency effects, Stroop-like congruency effects appear to result from processing along the same kind of pathway as task-switching congruency effects.

Stroop-like and task-switching congruency effects may be variations of the same phenomenon, with effects in reaction time indicating time needed to resolve competition resulting from categorization of two attributes of the same stimulus. In the Stroop context, one category is automatically activated due to overlearning while a different category is active due to its relationship to the currently-instructed task. In the task-switching context, two categories are active because each category relates to an attribute of the stimulus that can be categorized according to one of the potentially-relevant tasks recently presented. Though task-switching congruency effects in this experiment appeared to be influenced by overlearning, these effects did not differ across epochs within the mixed runs, mirroring previous work showing that within-session practice did not increase congruency effects (Meiran & Kessler, 2008). The present experiment was unable to determine whether small congruency effects in the Control condition appeared as a result of the first few instances of assigning a stimulus according to a rule associated with the opposing task.

Asymmetric switch costs favoring the less dominant task were significant only for Stroop-like conditions, consistent with previous reports (Monsell et al., 2000; Rubinstein et al., 2001). This result supports the idea that the pathway associated with the dominant task in Stroop-like conditions must be strongly suppressed to allow accurate response on non-dominant task trials. Carryover of this inhibition in trials that require switching to the dominant task results in particularly slow reaction times. The effect of switching on congruency effects was also modified by task. Congruency effects were larger on switch compared to nonswitch trials only for the dominant task in Stroop-like conditions. This pattern may be due to the dominant task being particularly strong on nonswitch trials, for which the category activated by the given stimulus for the current task instruction is the same as the category that is automatically activated due to

overlearning. This leads to relatively fast responses even on incongruent trials, as competition from the alternative category is relatively weak and easy to resolve. On switch trials, however, congruency effects are large because the attribute of the stimulus to be categorized is that associated with the strongly inhibited task set and not with the task set activated on the previous trial. This leads to substantial interference on incongruent trials, which must be resolved before responding.

Although this experiment suggests that congruency effects are larger in the presence of Stroop-like interference, the comparison conditions differ from each other in potentially important ways unrelated to the presence of pre-existing associations. Both the Numerical and Spatial conditions use verbal materials and a single, integrated stimulus. The Control condition uses nonverbal materials and requires a judgment to be made across two separate spatial locations when considering which shape is larger. Furthermore, though these data indicate that response slowness does not drive the RT congruency difference here, a response slowing account cannot be completely ruled out since both the Spatial and Numerical conditions are at least somewhat slower than the Control condition.

This experiment also cannot speak to the stage at which the congruency effect arises. Though I have presented a distinction according to overlearned stimulus-to-category associations based on the fact that increased congruency effects occur both in the Spatial condition and the Numerical condition, it is also clear that most Stroop-like conditions involve a level of automaticity in the category-to-response mapping. In the case of the traditional color word Stroop, the verbal response "blue" automatically comes about from the semantic concept of "blue." Evidence for a role of strong category-to-response associations in the Stroop effect comes from the fact that congruency effects are larger when there is conflict both at the semantic level and the response level ("blue" in red ink when blue and red are mapped to different hands) than when there is conflict only at the semantic level ("blue" in green ink when blue and green are mapped to the same hand; De Houwer et al, 2003)

In the present experiment, I have presented the Spatial condition as having strong stimulus-category mappings and strong category-response mappings due to the fact that bimanual response is made using a left-hand key press (z) or a right-hand key press (/). I have presented the Numerical condition, by contrast, as having only strong stimulus-category associations, indicating that the stimulus-category link leads to the amplified congruency effect. However, this may be an oversimplification. For all participants "1" was assigned to the z key and "3" was assigned to the / key. Since numbers tend to be mentally represented on a number line and all participants were fluent English speakers used to reading left to right, it could be argued that the category-to-response mapping for 1 to the left hand and 3 to the right hand may also be overlearned (Dehaene et al., 1993). Future experiments will investigate the stage at which the congruency effect occurs and replicate the findings from this experiment with conditions in which stimuli are equated across the other dimensions mentioned above.

Chapter III

Contribution of Overlearning to Task-Switching Congruency Effects

Objective

The present experiment attempted to address potential confounds in Experiment 1 by comparing conditions which differed in the presence of pre-existing stimulus-category associations but did not differ in other stimulus properties or overall difficulty. It also uses nominally nonverbal stimuli, to demonstrate that the effects seen in E1 are not specific to verbal conditions.

Method

Participants.

Twenty-four undergraduates (12 female; mean age = 18.81, SD = 1.28) participated for partial course credit.

Stimuli.
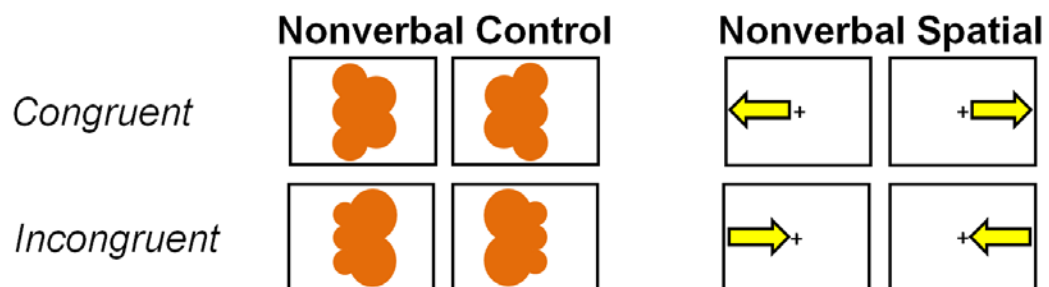
Figure 3.1. Experiment 2 conditions. There were two congruent and two incongruent stimuli repeated randomly throughout each condition. Color indicated the currently-relevant task.

Figure 3.1 illustrates stimuli for each condition: Nonverbal Control and Nonverbal Spatial. Current task was again indicated by the color of the stimulus. (1) In the Nonverbal Control condition, participants indicated which side of the shape was taller or which side had more bumps. (2) In the Nonverbal Spatial condition, participants responded to the direction the arrow was pointing or its position on the screen. The Nonverbal Control condition provides a conceptual replication of the Control from Experiment 1 using a single, spatially-integrated stimulus. The Nonverbal Spatial condition provides a conceptual replication of the Spatial condition from Experiment 1 using nonverbal stimuli.

3.2.1 Nonverbal Control
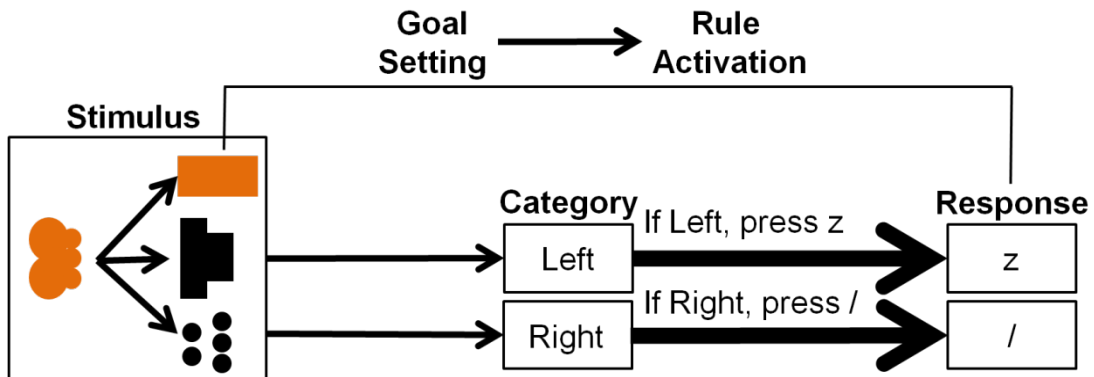
3.2.2 Nonverbal Spatial
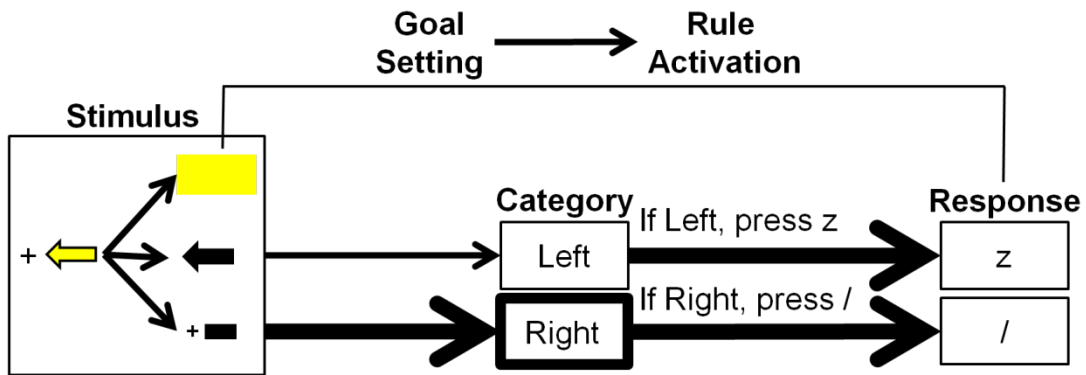
Figure 3.2. Representation of proposed model for each condition in Experiment 2. Each stimulus is first broken into component attributes (e.g., color, height of each side of the shape, and number of bumps on each side of the shape for the Nonverbal Control condition). The color attribute serves as a cue, allowing for goal shifting/maintenance. One stimulus attribute (e.g., relative height of each side of the shape) allows the stimulus to be assigned to a position-based category according to the current goal. The other stimulus attribute may also lead to the same semantic category (congruent trial) or the opposing category (incongruent trial). Each category is mapped to a behavioral response. Strong connections are represented by thicker lines and represent highly-practiced associations.

Procedure.

The procedure was similar to that of Experiment 1 with a few exceptions. (1) Participants completed two additional mixed runs for a total of eight runs per condition. (2) Stimuli were on the screen for up to 3000 ms. (3) Participants received self-paced and timed trials of response mapping practice prior to each

new pure run and prior to the first mixed run. (4) Task practice was increased to at least sixteen trials before each pure run (eight self-paced and eight timed) and at least thirty-two trials (sixteen self-paced and sixteen timed) before each mixed run.

Results

Filters were applied as described for Experiment 1. Reaction times are presented here, but means and statistics for congruency effects in accuracy, log-transformed accuracy, and combined z-scores of reaction time and error rate are presented in Appendices B, C, and D. Complete reaction time results for Experiment 2 are shown in Table 3.1.

		Congruent			Incongruent		
		Pure	**Nonswitch**	**Switch**	**Pure**	**Nonswitch**	**Switch**
Nonverbal Control	**More**	476	628	780	451	654	831
		(92)	(122)	(174)	(73)	(186)	(185)
	Taller	463	627	762	444	667	836
		(78)	(112)	(161)	(72)	(154)	(179)
Nonverbal Spatial	**Pointing**	455	547	656	513	624	744
		(60)	(112)	(166)	(148)	(144)	(172)
	Position	333	540	666	337	592	774
		(51)	(112)	(167)	(66)	(114)	(186)

Table 3.1 Experiment 2 reaction time means and standard deviations for all conditions. Means and corresponding standard deviations are presented in milliseconds.

Nonverbal Spatial condition, but not Nonverbal Control condition, shows Stroop-like properties.

As the current conditions are assumed to be conceptually equivalent to the conditions in Experiment 1, it was necessary to confirm that the Nonverbal Spatial condition but not the Nonverbal Control condition showed Stroop-like interference in the single-task (pure) runs. Only the Nonverbal Spatial condition

showed a disparity in automaticity between the two component tasks as responses were faster and more accurate for the position task (RT: $F_{(1,23)}$ = 72.69, $p < .001$; Accuracy: $F_{(1,23)}$ = 8.32, $p < .01$). The two tasks in the Nonverbal Control condition did not differ significantly in difficulty (RT: $F_{(1,23)}$ = .57, $p = .46$; Accuracy: $F_{(1,23)}$ = 1.22, $p = .28$). Also like the conditions in Experiment 1, only the Nonverbal Spatial condition showed Stroop-like congruency effects in the single-task runs consistent with overlearning of one task. Specifically, the Nonverbal Spatial condition showed a main effect of congruency, $F_{(1,23)}$ = 8.16, $p < .01$, which was present only for the pointing task (Task x Congruency effect, $F_{(1,23)}$ = 6.42, $p < .05$). The Nonverbal Control condition did not show Stroop-like interference. In fact, as in the Control condition from Experiment 1, incongruent trials were significantly faster than congruent trials, $F_{(1,23)}$ = 12.25, $p < .005$, on both tasks (Task x Congruency effect, $F_{(1,23)}$ = .16, $p = .69$). Based on these results, I compared task-switching congruency effects in the Nonverbal Control and Nonverbal Spatial conditions based on a difference in the presence of additional Stroop-like interference.

Task-switching and Stroop-like congruency effects are not additive.

As in Experiment 1, the Condition x Congruency x Switch interaction was not significant, $F_{(1,23)}$ = .03, $p = .86$. The Congruency x Switch interaction was present for both conditions (Nonverbal Control: $F_{(1, 23)}$ = 4.19, $p = .05$; Nonverbal Spatial: $F_{(1, 23)}$ = 5.25, $p < .05$). Therefore, congruency effects were again averaged across switch and nonswitch trials. If the RT differences in congruency effects described in Experiment 1 were due to superficial stimulus differences, we would expect that making both sets of stimuli integrated and nonverbal would result in similar RT congruency effects in both conditions. This was not the case: The Condition X Congruency interaction was significant for reaction time, $F_{(1,23)}$ = 7.95, $p < .05$ (Figure 3.3). This interaction was present across participants as 18 out of 24 participants showed larger congruency effects in the Nonverbal Spatial condition than in the Nonverbal Control condition. Importantly, the congruency effect was much larger in the Nonverbal Spatial

condition, and the effect size for the RT congruency effect in the Nonverbal Spatial condition was even larger than that of the Spatial and Numerical conditions in Experiment 1 (Nonverbal Spatial η^2_p = .79; Spatial η^2_p = .65; Numerical η^2_p = .63).

Although the congruency effects were larger in the Nonverbal Spatial (Stroop-like) condition, they were present at significant levels for both conditions: Nonverbal Control condition, $F(1, 23) = 12.78$, $p < .005$, with 20 out of 24 participants showing positive congruency effects; Nonverbal Spatial condition, $F(1, 23) = 84.91$, $p < .001$ with all 24 participants showing positive congruency effects. Correlations between congruency effects in the Nonverbal Control and Nonverbal Spatial conditions were weak ($r(21) = .22$, $p = .32$ after dropping one outlier, $r(22) = .50$, $p < .05$ with the outlier included). This again is consistent with previous findings of weak and inconsistent correlations between congruency effects across conditions in both task-switching (Yehene & Meiran, 2007) and Stroop (Shilling et al., 2002; Ward et al., 2001) procedures and supports the idea that congruency effects are dependent on the strength of stimulus-to-category associations which differ across conditions for each individual.

Also similar to Experiment 1, RT congruency effects in the present experiment were not related to response slowness. Even though the responses in the Nonverbal Spatial condition were a bit faster overall in the mixed runs than those in the Nonverbal Control condition (643 vs. 723 ms), the congruency effect was much larger for the Nonverbal Spatial condition. Taken together, the congruency effects observed in Experiment 1 and 2 indicate that overlearned stimulus-to-category associations play an important role in the size of task-switching congruency effects.
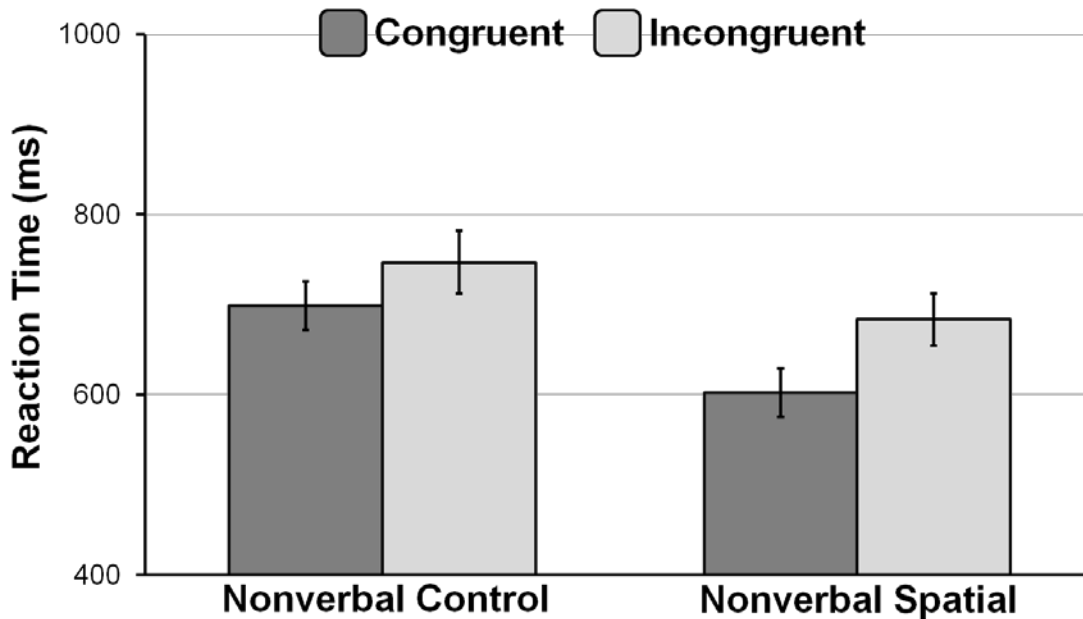
Figure 3.3. Congruency effects are larger in the presence of Stroop-like interference.

The magnitude of the congruency effect is predicted by the magnitude of overlearning in the Stroop-like condition.

Further evidence that overlearning contributes to the large congruency effects in the Nonverbal Spatial condition comes from individual differences in the automaticity of one task. Participants who showed large differences between single-task reaction time on pointing trials and single-task reaction time on position trials, indicating a stronger dominance of the position task, demonstrated larger congruency effects in the mixed task runs, $r(22) = .61$, $p < .005$. This effect remained significant once an outlier was removed, $r(21) = .42$, $p < .05$. (See Figure 3.4 for the correlation after outlier removal.) Consistent with the asymmetric congruency effects presented in Experiment 1, the relationship between relative dominance of the position task and magnitude of the congruency effect was only significant (after outlier removal) for trials that required a switch to the position task, $r(21) = .45$, $p < .05$. When the position task is highly automatized, strong inhibition of the corresponding task set on pointing trials leads to a higher level of interference when the position task becomes relevant following the pointing task.
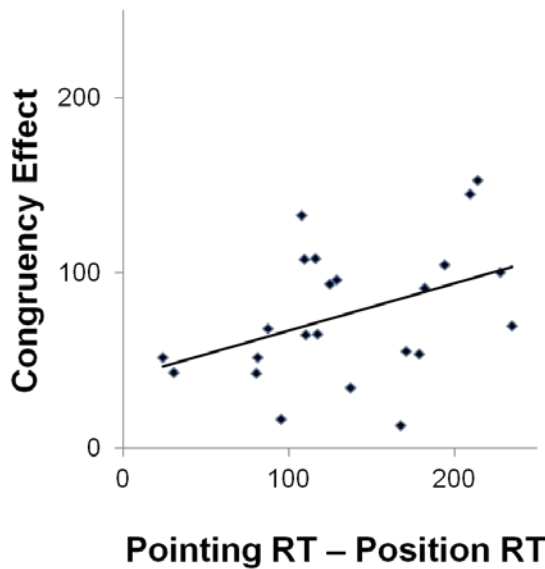
Figure 3.4 Relative dominance of one task predicts congruency effects. The difference between reaction time on pointing trials and the reaction time on position trials in the single-task runs is correlated with the magnitude of the congruency effect (incongruent – congruent) on trials in the mixed-task runs. Effects are presented in milliseconds.

Reaction time congruency effects did not change significantly within the mixed runs.

As in Experiment 1, there was no evidence of practice-related increases in congruency effects across the mixed runs in the Nonverbal Control condition (Figure 3.5). Reaction times from the mixed runs were separated by pairs (excluding the middle two runs) and submitted to a Time (first third, last third) x Congruency (congruent, incongruent) ANOVA to examine changes in the congruency effect across the mixed runs. Congruency effects in the first two mixed runs did not differ from those in the last two mixed runs, $F(1, 23) = .04$, $p = .85$. In Experiment 1, I described two possible explanations for the absence of a gradual, practice-related increase in congruency effects in a single session. The first possibility is that abstract response codes must be consolidated in long-term memory over a night's sleep to create a congruency effect (as proposed by Meiran). The second possibility is that congruency effects can appear quickly, after only a few instances of assigning a particular stimulus to a category in the

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mixed-task context. The latter explanation would fit with results reporting that priming effects in task-switching may be present after only a single instance of categorizing a stimulus (Waszak et al., 2003). This explanation would predict that congruency effects would be substantially larger in the mixed runs than in the practice for the mixed runs during which participants first categorize individual stimuli in a multiple-task context. In other words, practice effects may have stabilized by the time that participants are in the mixed runs, and have no further effect on performance within those runs. However, such effects may be more evident when examining participants' first exposure to the stimuli in the mixed-task context – that is, during the practice for those runs.

In the first experiment, there were too few practice trials to examine this possibility reliably. However, in this experiment, participants completed at least 32 practice trials – 16 early practice and 16 late practice. When looking at all correct early practice trials, there was no positive effect of congruency. Potentially due to the variability in RT estimates for the practice, the congruency effect in the first third of the experiment was still not significantly larger than the congruency effect during initial mixed-task practice, $F(1, 23) = .95$, $p = .34$. It is important to note that these early practice trials were fundamentally different from task trials as they were self-paced with no time limit and provided feedback after every trial, but the results here suggest that congruency effects may appear after very few instances of categorizing a stimulus in the mixed-task context.
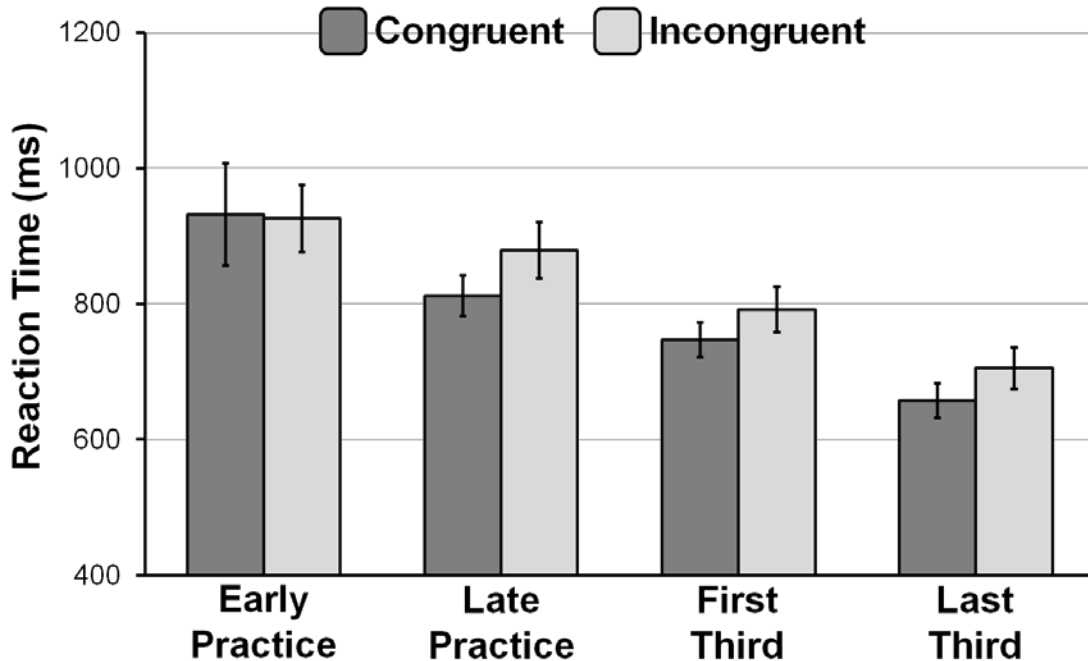
Figure 3.5. Congruency effects in the Nonverbal Control condition increase from initial practice to the mixed runs. Early practice trials are the first 16 trials, in which stimuli are assigned to categories in the mixed-task context and are self-paced with no time limit. Late practice trials are the first set of 16 timed practice trials. First third trials are from the first two mixed-task runs. Last third trials are from the last two mixed-task runs.

Asymmetry in switch costs and congruency effects.

In Experiment 1, significant paradoxical asymmetry was found in the Stroop-like conditions, but not in the Control condition. There was a significant task-based asymmetry in switch costs for the Nonverbal Spatial condition, $F(1, 23) = 8.09$, $p < .01$, such that switch costs were larger for switching to the dominant position task. In contrast, there was no significant Switch x Task interaction for the Nonverbal Control condition, $F(1, 23) = .60$, $p = .44$. These results are consistent with previous work indicating that strong disparities in automaticity between tasks lead to paradoxical switch cost asymmetry (e.g., Allport et al., 1994; Yeung & Monsell, 2003; Koch, Prinz, & Allport, 2005).

In Experiment 1, I showed that the Congruency X Switch interaction in the Stroop-like conditions was larger for the dominant task than for the nondominant task. The same comparison was examined here, for both the Nonverbal Control and Nonverbal Spatial conditions (Figure 3.6). As expected from the fact that the

Nonverbal Control condition did not have a dominant task, the Congruency x Switch x Task interaction for that condition did not approach significance, $F(1, 23) = .14$, $p = .72$. Instead, the Congruency x Switch interaction was numerically present, but not statistically significant, for both tasks (More: $F(1, 23) = 1.70$, $p = .21$, Taller: $F(1, 23) = 2.78$, $p = .11$). In the Nonverbal Spatial Stroop-like condition, in which the position task was dominant, the Congruency x Switch x Task interaction did not reach statistical significance, $F(1, 23) = 1.35$, $p = .26$; however, the difference between congruency effects on nonswitch and switch trials was numerically larger for the dominant position task, similar to the pattern seen in the Stroop-like conditions in Experiment 1. In addition, the Switch x Congruency effect was significant for the position task, $F(1, 23) = 8.79$, $p < .01$, but not for the pointing task, $F(1, 23) = .17$, $p = .68$.
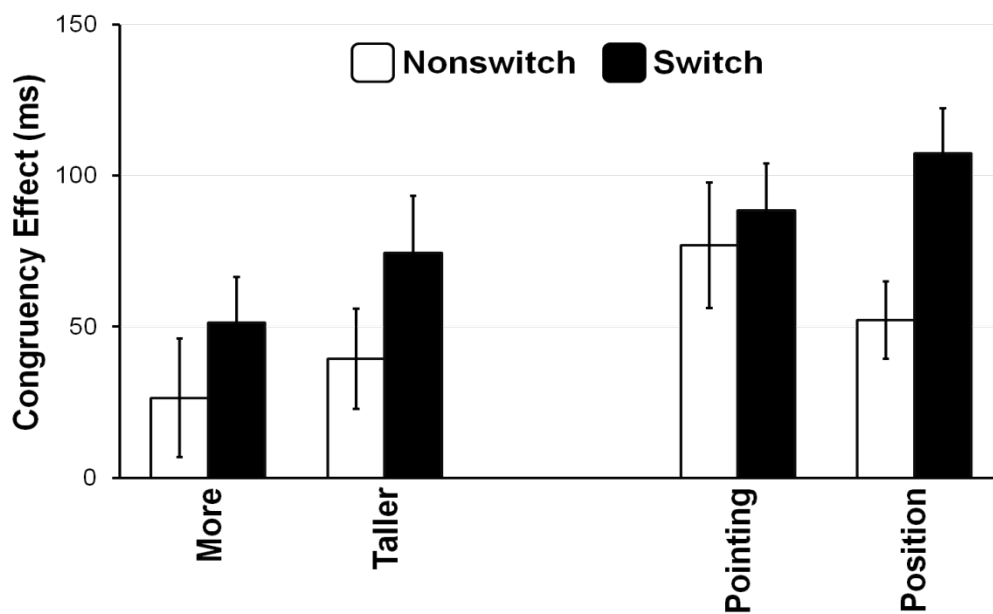
Figure 3.6. The switch difference in congruency effects is larger for the dominant (position) task in the Stroop-like condition.

Discussion

The present results replicated the central finding of Experiment 1: the task-switching RT congruency effect was larger in the presence of an overlearned task. The congruency effect was present at a significant level even in the Nonverbal Control condition, but was significantly larger in the Nonverbal

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Spatial condition, in which responding to the position dimension of the stimulus was highly automatic. This replication was important as it ruled out the possibility that the findings in Experiment 1 were due to superficial stimulus differences between the conditions of interest. The present experiment also provided support for the idea that exaggerated congruency effects were not the result of response slowing since responses were overall faster for the Nonverbal Spatial condition which showed larger congruency effects. The present experiment also extended the findings from Experiment 1 by showing that those individuals who showed larger differences in automaticity of the two tasks in the single-task runs also demonstrated larger congruency effects in the mixed runs, supporting the idea that larger congruency effects in the Nonverbal Spatial condition were related specifically to the overlearning of one task.

The Nonverbal Control condition showed significant congruency effects even in the absence of a pre-experimentally overlearned task. Though these effects were similar across the mixed runs, arguing against a gradual increase in congruency effects as a function of increased practice, congruency effects were not present during initial practice on the mixed runs. This result is consistent with the idea that congruency effects arise when a particular stimulus must be assigned to a category based on one attribute after it has been assigned to a different category based on a different attribute on a previous trial (Kiesel et al., 2007). The present experiment cannot address whether these effects are stimulus-specific. However, other authors have reported larger congruency effects for stimuli that are repeated more often (Kiesel et al, 2007). Larger switch costs have also been observed due to stimulus-specific priming from previous trials. Waszak and colleagues (2003) showed participants a series of line drawings of objects with the printed name of another object presented over the line drawing. Participants showed larger switch costs when reading the word if they had previously named the object, even if object-naming had occurred only once for a particular stimulus presented several minutes before the trial of interest. This finding suggests that participants may be showing congruency

effects due, at least partly, to previous experience categorizing a stimulus based on the currently-irrelevant attribute of the stimulus.

Chapter IV

The Source of the Task-Switching Congruency Effect

Objective

Meiran and Kessler (2008) argued that the activated codes in long-term memory underlying RT congruency effects in task-switching paradigms (but not Stroop or Simon paradigms) involve mediation through categories (See Figure 1.1). That is, stimuli are assigned first to an abstract semantic category like "odd" or "larger than 5." That abstract category is then linked to a specific motor response. Previous work has not specifically addressed whether RT congruency effects result due to assigning a stimulus to a semantic category or due to translating that category mapping into a response. Experiments 1 and 2 provide support for the idea that congruency effects in reaction time are influenced by overlearning in Stroop-like tasks. I have suggested that this overlearning may influence assignment of a stimulus to a category, a claim that is supported by the development of substantial congruency effects early in mixed-task practice for a condition with experimentally-defined stimulus-category relationships.

In this experiment, I explore the effects of manipulating stimulus-category associations. If stronger stimulus-category associations contribute to larger congruency effects in RT, congruency effects should be smaller for conditions in which each trial involves assignment of a novel stimulus to the abstract category than for conditions in which a single stimulus may be assigned to different categories on different trials. The present experiment compares a condition with novel stimulus-category associations to one with overlearned stimulus-category associations.

Method

Participants.

Twenty-four undergraduates (19 female; mean age = 18.43, SD = 0.73) participated for partial course credit. None of the participants had previously participated in Experiment 1 or 2.

Stimuli.

Figure 4.1. Experiment 3 conditions. In the Spatial condition, two congruent and two incongruent stimuli are repeated randomly throughout the condition. In the Verbal Control condition, half of the stimuli are congruent and half are incongruent, but individual words do not repeat in the condition.

Figure 4.1 illustrates stimuli for each condition: Verbal Control and Spatial. (1) In the Verbal Control condition, participants indicated whether the referent of a word was manmade or natural or whether it was larger or smaller than a computer screen. Importantly, this condition used unique words on each trial such that each stimulus was assigned only once and to a single abstract category. (2) The Spatial condition used stimuli identical to those in the Spatial condition in Experiment 1. This condition re-used the same two words and two spatial locations throughout the experiment requiring repeated assignment of single stimulus a position-based category. These two conditions thus provide a direct comparison between a situation with novel stimulus-category associations to one in which the stimulus-category and category-response associations are overlearned (See Figure 4.2).

4.2.1 Verbal Control
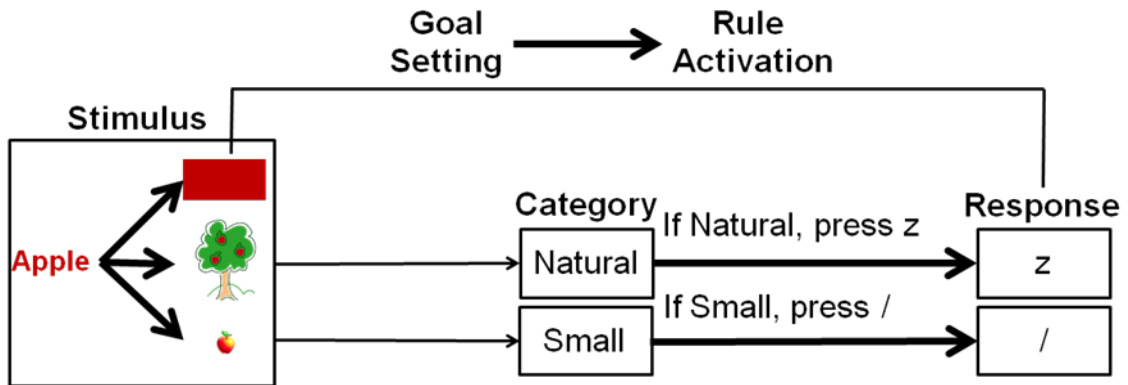
4.2.2 Spatial
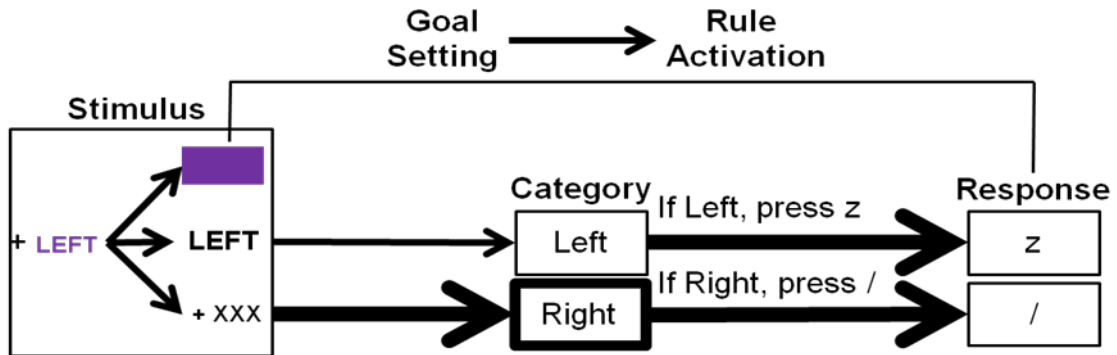
Figure 4.2. Representation of proposed model for each condition in Experiment 3. Each stimulus is first broken into component attributes (color of the text, origin of the referent (e.g., an apple is natural because it grows on a tree), and size of the referent (e.g., an apple is small), for the Verbal Control condition). The text-color attribute serves as the cue for goal shifting/maintenance. One stimulus attribute (origin or size) is relevant to the goal and is supposed to serve as the basis for assigning the stimulus to the relevant semantic category and determining the response. The other stimulus attribute may lead to a category linked to the same response (congruent trial) or a category linked to the opposing response (incongruent trial). Each category is mapped to a behavioral response. In this experiment, stimulus-to-category mappings are novel for each stimulus in the Verbal Control condition, so stimulus-category connections are weak in that condition.

Procedure.

The procedure was identical to that of Experiment 2.

Results

Filters were applied in the same way as described for Experiments 1 and 2. Reaction times are presented here, but means and statistics for congruency effects in accuracy, log-transformed accuracy, and combined z-scores of reaction time and error rate are presented in Appendices B, C, and D, respectively. Complete reaction time results for Experiment 3 are shown in Table 4.1.

		Congruent			Incongruent		
		Pure	**Nonswitch**	**Switch**	**Pure**	**Nonswitch**	**Switch**
Verbal Control	**Origin**	928 (209)	1020 (233)	1442 (212)	895 (162)	994 (200)	1478 (244)
	Size	857 (164)	1095 (218)	1539 (213)	890 (194)	1103 (211)	1579 (309)
Spatial	**Meaning**	502 (105)	694 (131)	816 (144)	516 (85)	757 (162)	878 (158)
	Position	336 (42)	598 (131)	780 (123)	335 (45)	651 (161)	901 (157)

Table 4.1 Experiment 3 reaction time means and standard deviations for all conditions. Times are reported in milliseconds.

Spatial, but not Verbal Control, condition shows Stroop-like properties.

As with this condition in Experiment 1, the Spatial condition showed significantly slower reaction time on pure (single-task) trials for the meaning task than for the position task, $F(1,23) = 123.91$, $p < .001$ and a trend toward a Stroop-like congruency effect, $F(1,23) = 2.28$, $p = .11$ carried by the non-dominant meaning task (Task x Congruency: $F(1,23) = 3.59$, $p = .07$). Similar to previously presented Control conditions, the Verbal Control condition showed a trend toward one task being less difficult as reaction times were faster for the size discrimination, $F(1,23) = 2.78$, $p = .11$, but no indication of a Stroop-like congruency effect, $F(1,23) = .00$, $p = .98$.

Task-switching congruency effects are minimal when stimuli are novel on each trial.

As in the previous experiments, the Condition x Congruency x Switch interaction was not significant, $F(1, 23) = .15$, $p = .71$, due to the fact that the Congruency x Switch interaction was present for both conditions, though only significant for the Spatial condition (Verbal Control: $F(1, 23) = 1.88$, $p = .18$; Spatial: $F(1, 23) = 4.85$, $p < .05$). The primary evaluation of congruency effects was again collapsed across switch and nonswitch trials.

If the differences in RT congruency effects described in Experiment 1 and 2 were due to differences in experience with assigning a particular stimulus to a category, we would expect that the Verbal Control condition, in which stimulus-to-category associations were novel and not repeated, would result in little or no RT congruency effect. This was indeed the case: The Condition X Congruency interaction was highly significant, $F(1,23) = 8.91$, $p < .01$ (Figure 4.3) with 17 out of 24 participants showing a larger congruency effect for the Spatial condition than for the Verbal Control condition. The congruency effect for the Verbal Control condition did not approach statistical significance, $F(1, 23) = .61$, $p = .44$, whereas the size of the RT congruency effect for the Spatial condition was consistent with that found for the same task in Experiment 1, $F(1, 23) = 59.56$, $p < .001$. Performance of individual subjects was consistent with the means reported. A slight majority of participants (14 out of 24) showed a positive congruency effect in the Verbal Control condition while every participant showed a positive congruency effect in the Spatial Condition. Congruency effects in the Verbal Control condition were not related to those in the Spatial condition ($r(21) = .12$, $p = .57$).
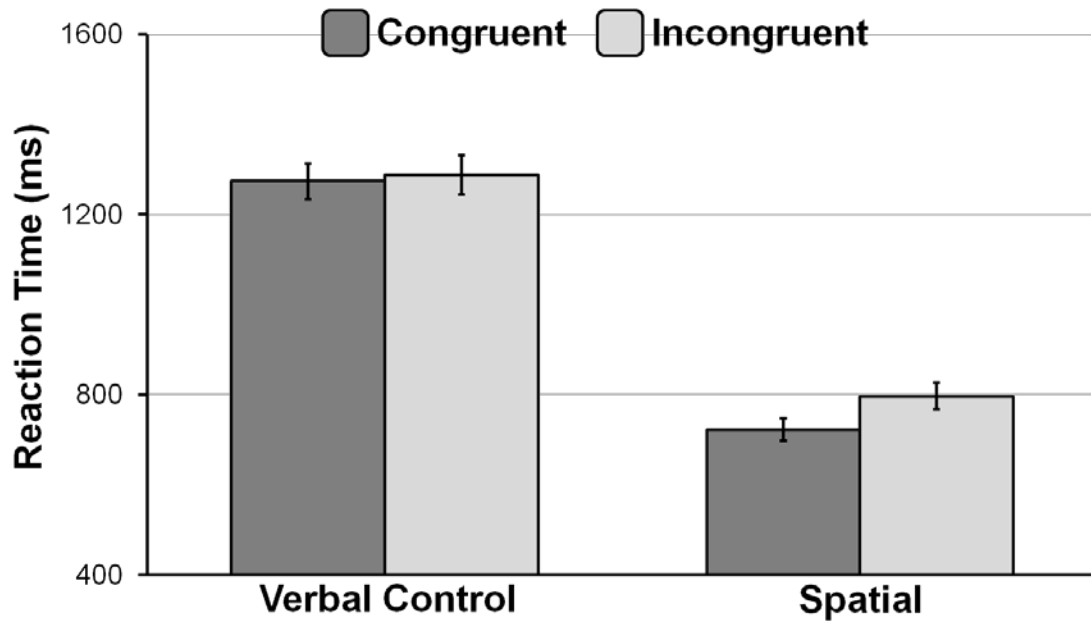
Figure 4.3. Congruency effects are small when stimuli are not repeated.

The lack of a significant RT congruency effect in the Verbal Control condition supports the idea that RT congruency effects can arise from assigning a stimulus to a category. If the current stimulus assignment conflicts with a previous assignment of that same stimulus to a different semantic category, for example assigning the word "right" on the left side of the screen to the "right" category rather than the overlearned "left" category, additional time is required to resolve interference at the level of the category and subsequently at the level of the response. Participants must overcome the automatic reactivation of the category that results from presentation of the stimulus. However, in the Verbal Control condition, the use of unique stimuli on each trial means that there is no prior stimulus-to-category assignment to conflict with the currently-relevant one. The lack of an RT congruency effect in the Verbal Control condition is particularly compelling given the overall long reaction time in this condition, a further indication that size differences in RT congruency effects are not related to response time.

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Congruency effects in the Novel Stimulus condition do not increase after practice.

In Experiment 2, I observed a nonsignificant increase in Nonverbal Control congruency effects from initial practice to the first two mixed-task runs. (The congruency effect was only positive during the congruency effect in the mixed-task runs.) Though the practice trials differed in timing from the mixed-task trials, this numerical difference suggests that congruency effects may arise after very little experience assigning a stimulus to a particular category in the mixed-task context. The same comparison was explored in the present experiment. Since stimuli are not repeated in the Verbal Control condition, categorization of a single stimulus is not repeated on different trials. If it were true that the numerical increase in congruency effects observed in the Nonverbal Control condition was due to experience assigning a stimulus to a category during the practice, we would expect that there would be no numerical increase in the congruency effect for the Verbal Control condition.

The congruency effect differed significantly between initial practice and the first two mixed runs, $F(1,23) = 9.97$, $p < .005$, but that difference was due to a decrease in the congruency effect after initial practice (Figure 4.4). The large congruency effect seen in initial practice may seem surprising, but the Verbal Control condition was difficult for participants (as evidenced by the overall long reaction times for this condition and the fact that participants frequently chose to repeat the practice). Participants reported difficulty remembering which task was represented by each color in this condition, which could explain why participants showed particularly long reaction times on trials for which the response differed depending on the currently-relevant task. Evidence that this large initial-practice congruency effect was an artifact of difficulty acquiring the instructions associated with this condition comes from smaller congruency effects in later practice trials. Regardless of the source of large congruency effects in initial practice, the present results clearly do not demonstrate an increase in congruency effects as the result of initial practice like that shown by the Nonverbal Control condition in Experiment 3. These data give additional weight

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to the argument that congruency effects arise, at least in part, from repeated assignment of a specific stimulus to a category.
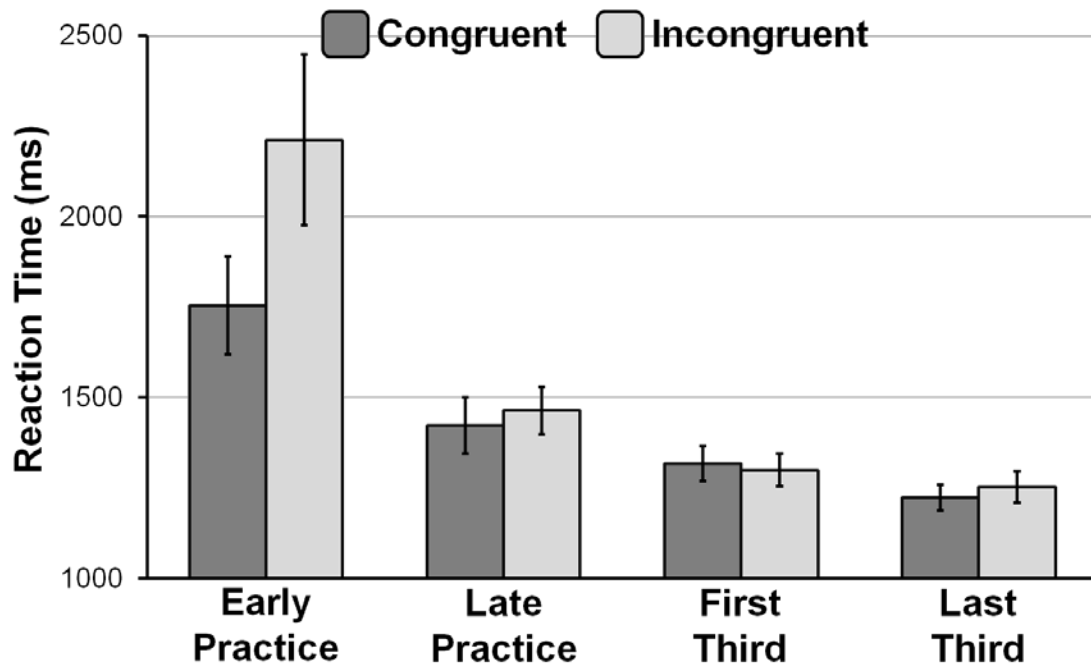
Figure 4.4. Congruency effects in the Novel Stimulus condition do not increase over time. Early practice trials are the first 16 trials, in which stimuli are assigned to categories in the mixed-task context and are self-paced with no time limit. Late practice trials are the first set of 16 timed practice trials. First third trials are from the first two mixed-task runs. Last third trials are from the last two mixed-task runs.

Asymmetry in switch costs and congruency effects.

As in the first two experiments, there was no significant Switch x Task interaction for the Verbal Control condition, $F(1, 23) = .03$, $p = .86$. There was a significant task-based asymmetry in switch costs for the Spatial condition, $F(1, 23) = 60.84$, $p < .001$, because switch costs were larger for switching to the dominant position task.

In Experiment 1, I showed that the Switch (nonswitch, switch) x Congruency (congruent, incongruent) interaction differed by task in the Spatial condition used here. In the present experiment, I replicated those results (Figure 4.5). The Congruency x Switch x Task interaction was significant for the Spatial condition, $F(1, 23) = 5.20$, $p < .05$. The difference between congruency effects on

nonswitch and switch trials was larger for the dominant position task. The Switch x Congruency effect was significant for the position task, $F(1, 23) = 7.94$, $p < .05$, but not for the meaning task, $F(1, 23) = .00$, $p = .95$. Conceptually replicating the findings from the first two experiments, the Congruency x Switch x Task interaction was not significant for the Verbal Control condition, $F(1, 23) = .21$, $p = .65$. The Switch x Congruency interaction was not significant for either task (origin: $F(1, 23) = 2.88$, $p = .10$, size: $F(1, 23) = .32$, $p = .58$).
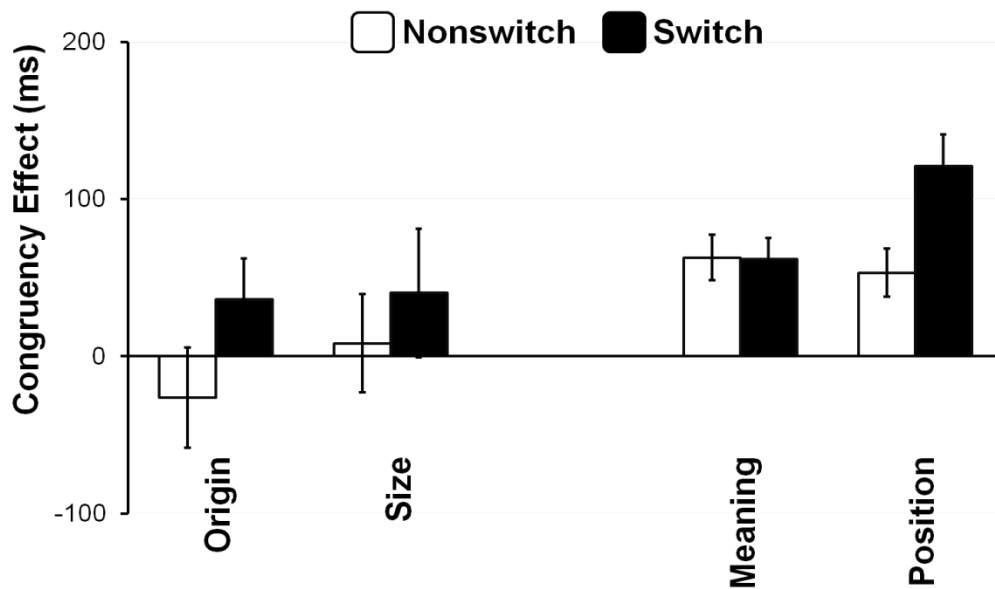
Figure 4.5. Spatial condition shows characteristic asymmetry. Congruency effects were larger on switch trials for the dominant position task in the Spatial condition.

Discussion

The present experiment demonstrated that congruency effects are negligible when individual stimuli are not repeated across trials. This finding is consistent with the idea that congruency effects arise when the stimulus one is currently assigning to a category was previously assigned to a different category. Presentation of the stimulus automatically activates the previously-relevant category leading to competition between the categories and subsequent responses. The lack of a significant congruency effect in the Verbal Control

condition here, which used novel stimulus-to-category assignments on every trial, contrasts with the significant congruency effect found in the Nonverbal Control condition in Experiment 2. In the Nonverbal Control condition, significant congruency effects occurred even in the absence of pre-existing overlearning because the same set of stimuli were assigned repeatedly to competing categories. As support of this explanation, the congruency effect for the Nonverbal Control condition in Experiment 2 arose only after practice, whereas in the present experiment, congruency effects seen early in the session diminished after practice. The difference observed between these two control conditions is interesting given that in many other ways these conditions are conceptually equivalent (e.g., both show no significant single-task congruency effects).

However, several factors limit the degree to which the present results can be used to argue that interference resulting from previously-learned (either prior to the experiment or in the context of the task-switching procedure itself) stimulus-category associations is the primary source of congruency effects. The Verbal Control condition in the present experiment and the Nonverbal Control condition in Experiment 2, differ in stimulus material (though previous experiments have demonstrated that the influence of overlearning on congruency effects does not appear to vary according to whether stimuli are verbal or nonverbal). Within the present experiment, the Verbal Control and Spatial conditions differ at the level of response execution. The abstract categories assigned to each key differ across the two tasks for the Verbal Control condition but not for the Spatial condition. That is, in the Verbal Control condition, if the goal was to identify the origin of the referent, the left key might indicate "manmade," whereas if the goal was to identify the size of the referent, the left key might indicate "smaller." In contrast, the keys have fixed (and overlearned) meanings of "left" and "right" for the Spatial condition regardless of the current task instructions. Changes in response meanings have non-trivial effects of their own, making the comparison of the Verbal Control and Spatial conditions less than ideal (Mayr, 2001; Meiran, 2000b). Specifically, due to the bivalent responses, competition may exist at the level of the category on both congruent

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and incongruent trials in the Verbal Control condition, but only at the level of the response on incongruent trials. In the Spatial condition (and all conditions presented previously in this dissertation), responses were univalent – only one semantic category mapped to each response, so competition existed at the level of the category and subsequently at the level of the response only for incongruent trials. This distinction is important for our understanding of congruency effects as many studies of task-switching congruency effects use bivalent responses (e.g., Sudevan & Taylor, 1987, Rogers & Monsell, 1995). Experiment 4 was designed to address concerns about unintended differences between the Verbal Control and the Spatial Condition.

Chapter V

Repeated Stimulus Assignment Leads to a Congruency Effect

Objective

Smaller RT congruency effects in the Verbal Control condition of Experiment 3 relative to both the Spatial condition and to the earlier control conditions support the idea that RT congruency effects may be related to repeated assignment of a specific stimulus to a category. This final experiment tests that hypothesis directly by comparing two conditions that differ only in whether stimulus-category assignments are repeated while holding all other factors constant.

Method

Participants.

Twenty-four undergraduates (9 female; mean age = 18.63, SD = 0.65) participated for partial course credit. None of the participants had previously participated in this line of experiments.

Stimuli.
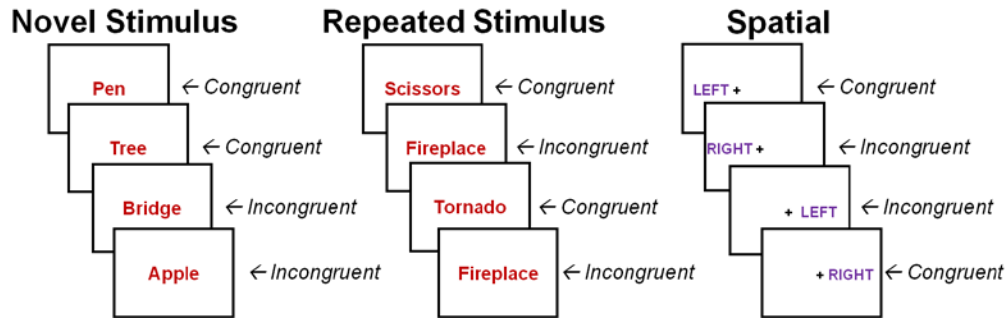
Figure 5.1. Experiment 4 conditions. In the Spatial and Repeated Stimulus conditions, two congruent and two incongruent stimuli are repeated randomly throughout each condition. In the Novel Stimulus condition, half of the stimuli are congruent and half are incongruent, but individual words do not repeat in this condition.

Figure 5.1 illustrates stimuli for each condition: Verbal Control: Novel Stimulus, Verbal Control: Repeated Stimulus, and Spatial. (1) The Novel Stimulus condition used stimuli identical to those used in Experiment 3. A novel word was presented for categorization on each new trial. (2) The Repeated Stimulus condition used the same tasks and cue colors as the Novel Stimulus condition, but presented the same four words (two congruent and two incongruent) repeatedly, to be comparable to the repeated stimulus-category assignment of our other conditions. (3) The Spatial condition used stimuli identical to those in the Spatial condition in Experiments 1 & 3 and was included as a within-subjects positive control for the presence of the RT congruency effect. Comparisons of these conditions in the context of the proposed model are shown in Figure 5.2.

5.2.1 Novel Stimulus Control
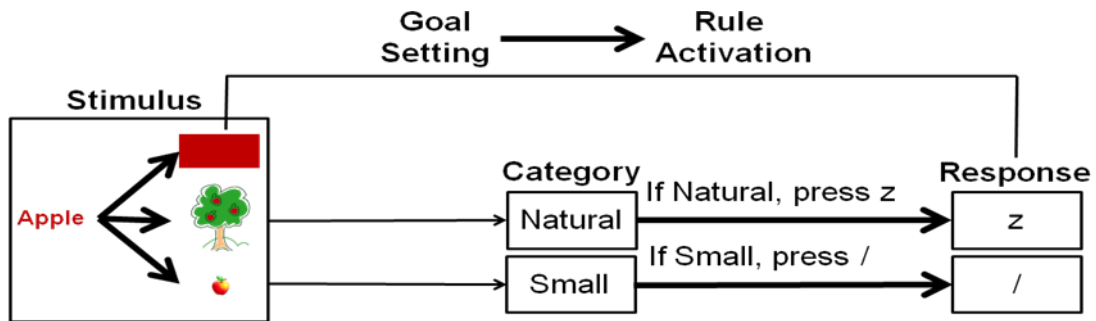
5.2.2 Repeated Stimulus Control
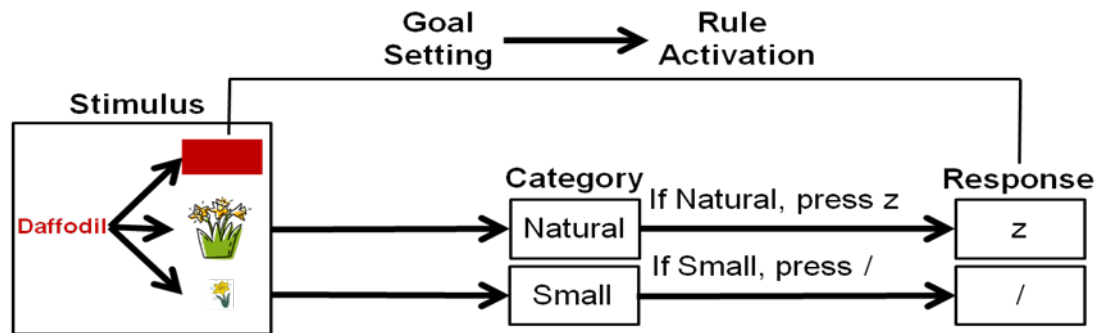
5.2.3 Spatial
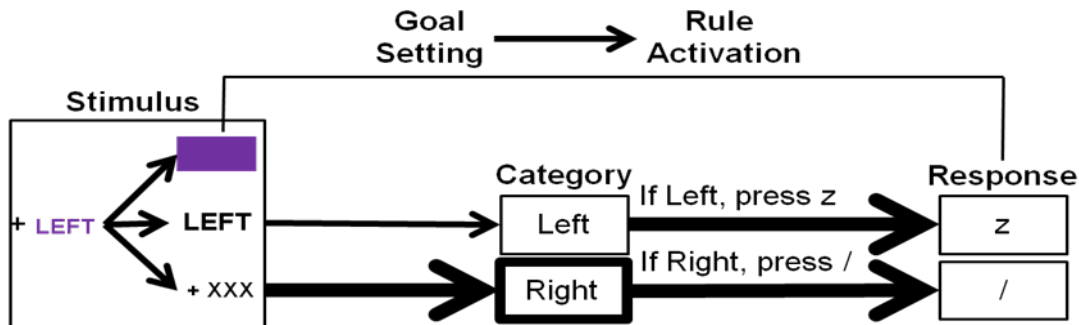
Figure 5.2. Representation of proposed model for each condition in Experiment 4. Each stimulus is first broken into component attributes (e.g., text color, origin of the referent (e.g., a daffodil is natural because it grows out of the ground), and size of the referent (e.g., a daffodil is small) for the Repeated Stimulus condition). The text-color attribute serves as a cue, allowing for goal shifting/maintenance. One stimulus attribute (e.g., origin of the daffodil) allows the stimulus to be assigned to a semantic category according to the current goal. The other stimulus attribute may lead to a same semantic category that activates the same response (congruent trial) or the opposing response (incongruent trial). Each category is mapped to a behavioral response. Stimulus-to-category mappings are novel for each stimulus in the Novel Stimulus condition, so stimulus-category connections are weak in that condition.

Procedure.

The procedure was similar to that of Experiments 2 and 3 except that words were presented for up to 2.5 seconds and there was no separate response-mapping practice.

Results

Filters were applied as in previous experiments. Reaction times are presented here, but means and statistics for congruency effects in accuracy, log-transformed accuracy, and combined z-scores of reaction time and error rate are presented in Appendices B, C, and D, respectively. Complete reaction time results for Experiment 4 are shown in Table 5.1.

		Congruent			Incongruent		
		Pure	**Nonswitch**	**Switch**	**Pure**	**Nonswitch**	**Switch**
Novel Stimulus	**Origin**	812 (116)	871 (142)	1317 (214)	832 (141)	913 (141)	1335 (203)
	Size	820 (116)	987 (137)	1361 (208)	846 (106)	1009 (130)	1406 (190)
Repeated Stimulus	**Origin**	648 (134)	816 (154)	1156 (281)	634 (128)	989 (211)	1328 (211)
	Size	617 (90)	797 (144)	1076 (236)	593 (77)	940 (163)	1290 (214)
Spatial	**Meaning**	477 (52)	623 (115)	767 (159)	494 (51)	664 (127)	826 (144)
	Position	325 (45)	536 (89)	735 (135)	323 (52)	580 (111)	869 (136)

Table 5.1 Experiment 4 reaction time means and standard deviations for all conditions. Times are in milliseconds.

Neither Control condition shows Stroop-like effects.

As observed with this condition in Experiments 1 and 3, the Spatial condition showed significantly slower reaction time on pure (single-task) trials for the meaning task than for the position task, $F(1,23) = 221.41$, $p < .001$ and a Stroop-like congruency effect, $F(1,23) = 5.11$, $p < .05$ carried by the non-dominant meaning task (Task x Congruency: $F(1,23) = 10.91$, $p < .005$.). In the Repeated Stimulus condition, in which both tasks were practiced equally, the two tasks had similar response times overall in the single-task runs, though there was a small numerical trend toward the size judgment being easier (641 ms vs. 605 ms, $F(1,23) = 2.16$, $p = .16$). These tasks showed a marginal congruency effect, $F(1,23) = 4.25$, $p = .05$, Consistent with the idea that the two practiced tasks were of approximately equal difficulty, the congruency effect was of equal size for both tasks (Congruency x Task interaction $F < 1$). The two tasks of the Novel Stimulus condition were also of equivalent difficulty (822 ms vs. 833 ms, $F < 1$, and did not show a significant congruency effect in the single-task runs, although there was a small numerical trend in this direction, $F(1,23) = 2.30$, $p = .14$.

The presence of a congruency effect during the single-task runs for the Repeated Stimulus condition and the trend in that direction for the Novel Stimulus condition was not expected based on the absence of congruency effects during single-task runs in the control conditions in previous experiments. One potential explanation for this finding is that each participant completed both the Repeated Stimulus and the Novel Stimulus conditions. Thus, in many cases, the single-task trials were being completed after a set of mixed-task runs on another condition using the same tasks.

To account for potential order effects on single-task run performance, I looked at Repeated Stimulus reaction times only for participants who completed the Repeated Stimulus condition first and at Novel Stimulus reaction times for only participants who completed the Novel Stimulus condition first. Removing these potentially confounding ordering effects yielded results more similar to those in the previous experiments. There was no significant difference in difficulty between the tasks in the single-task runs for either the Repeated Stimulus

condition, F < 1, or the Novel Stimulus condition, F(1,11) = 1.88, p = .20 (numerical difference favoring categorization based on the size of the referent). Neither condition showed a Stroop-like congruency effect in the pure runs. The Repeated Stimulus condition showed a numerical difference in the opposite direction, Congruency: F(1,11) = 2.03, p = .18; this did not interact with task, Congruency x Task: F < 1. There was no suggestion of a Stroop-like congruency effect in pure runs for the Novel Stimulus condition, and no interaction with the task used in each run, both F < 1. These results suggest that neither the Novel Stimulus nor the Repeated Stimulus conditions demonstrate Stroop-like effects in the single-task context. Thus, any increased congruency effect observed in the Repeated Stimulus condition during the mixed runs is likely related to the difference in the number of times a single stimulus was assigned to a category rather than unpredicted development of a Stroop-like asymmetry.

Task-switching congruency effects are nonexistent when stimuli are novel on each trial.

The Condition x Congruency x Switch interaction was again not significant, F(1.61, 36.99) = 1.18, p = .31 even though the Congruency x Switch interaction was only significant for the Spatial condition, F(1, 23) = 11.55, p < .005 (Novel Stimulus: F(1, 23) = .00, p = .98; Repeated Stimulus, F(1, 23) = 1.38, p = .25). Thus, congruency effects are again evaluated collapsed across switch and nonswitch trials.

In the mixed runs, the Condition x Congruency interaction comparing all three conditions (Spatial, Repeated Stimulus, Novel Stimulus) was significant, F(1.20, 27.58) = 20.72, p < .001 (Figure 5.3). Of particular interest to this experiment, congruency effects were larger for the Repeated Stimulus condition than for the Novel Stimulus condition, F(1, 23) = 13.45, p < .005, with 21 out of 24 participants showing larger congruency effects in the Repeated Stimulus condition. This result supports the idea that task-switching congruency effects in reaction time are related to repeated assignment of a specific stimulus to a response category. Unlike the results in Experiment 3, there was a significant

congruency effect in reaction time in the Novel Stimulus condition, $F(1,23) =$ 8.11, $p < .01$. The congruency effect was larger for the Repeated Stimulus condition, $F(1,23) = 40.10$, $p < .001$, and the Spatial condition, $F(1,23) = 64.99$, $p < .001$. As I will describe below (see also Figure 5.4), the small congruency effects found in the Novel Stimulus condition were likely due to previous exposure to the Repeated Stimulus condition.

Congruency effects were not reliably correlated between the Spatial condition and the Repeated Stimulus conditions, $r(22) = -.04$, $p = .85$ but were correlated between the Novel Stimulus and Spatial conditions, $r(22) = .49$, $p < .05$. Congruency effects in the Novel Stimulus and Repeated Stimulus conditions were significantly correlated, $r(22) = .41$, $p < .05$. This correlation between the Novel Stimulus and Repeated Stimulus conditions suggests that the re-use of the same tasks and types of stimuli across conditions may allow for correlations because the strength of the connection between a certain stimulus attribute and a category is consistent across conditions for each participant.
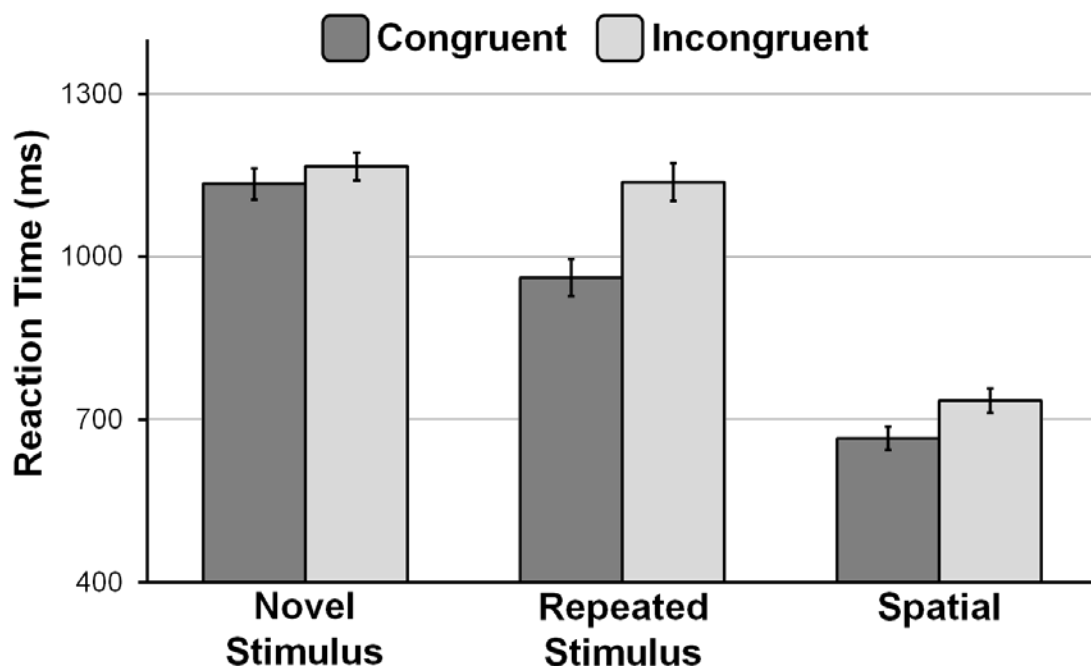
Figure 5.3. Congruency effects are smaller when stimuli are not repeated.

These results suggest that congruency effects in reaction time occur at the level of assigning stimuli to a semantic category. When a stimulus appears, it can be classified based on either of two attributes. In the Novel Stimulus condition, the stimulus can be assigned and a response can subsequently be executed without interference due to previous assignment of that stimulus to a different category. In the Repeated Stimulus condition, the category appropriate for the currently-irrelevant task is activated by the stimulus if the stimulus has previously been categorized according to the currently-irrelevant task in a mixed-task context.

Though the significant Condition x Congruency interaction reported here supports a role for assignment of a specific stimulus to a category, the strength of that inference is limited by the presence of a significant congruency effect in the Novel Stimulus condition. This effect was not observed in the previous experiment that used the Novel Stimulus condition, raising the possibility that exposure to the Repeated Stimulus condition affected processing in the Novel Stimulus condition. This appears to be the case (Figure 5.4). The Condition (novel, repeated) x Congruency (congruent, incongruent) x Order (repeated first, novel first) interaction was not significant, $F(1,22) = 1.20$, $p = .29$. However, an examination of congruent versus incongruent trials in the Novel Stimulus condition for participants who completed the Novel Stimulus condition before the Repeated Stimulus condition showed no effect of congruency, $F(1,11) = .00$, $p = 1.00$, with only 7 out of 12 participants showing a positive congruency effect. The effect of congruency in the Novel Stimulus condition was significant for participants who completed the Repeated Stimulus condition first, $F(1,11) = 44.13$, $p < .001$, with all 12 participants showing a positive congruency effect. The effect of congruency in the Repeated Stimulus condition was significant regardless of whether participants had previously completed the Novel Stimulus condition, $F(1,11) = 14.02$, $p < .005$ with 10 out of 12 participants showing a positive congruency effect, or not, $F(1,11) = 28.88$, $p < .001$ with 11 of 12 participants showing a positive congruency effect. Means separated by the order of presentation of each condition are shown in Tables 5.2 and 5.3.
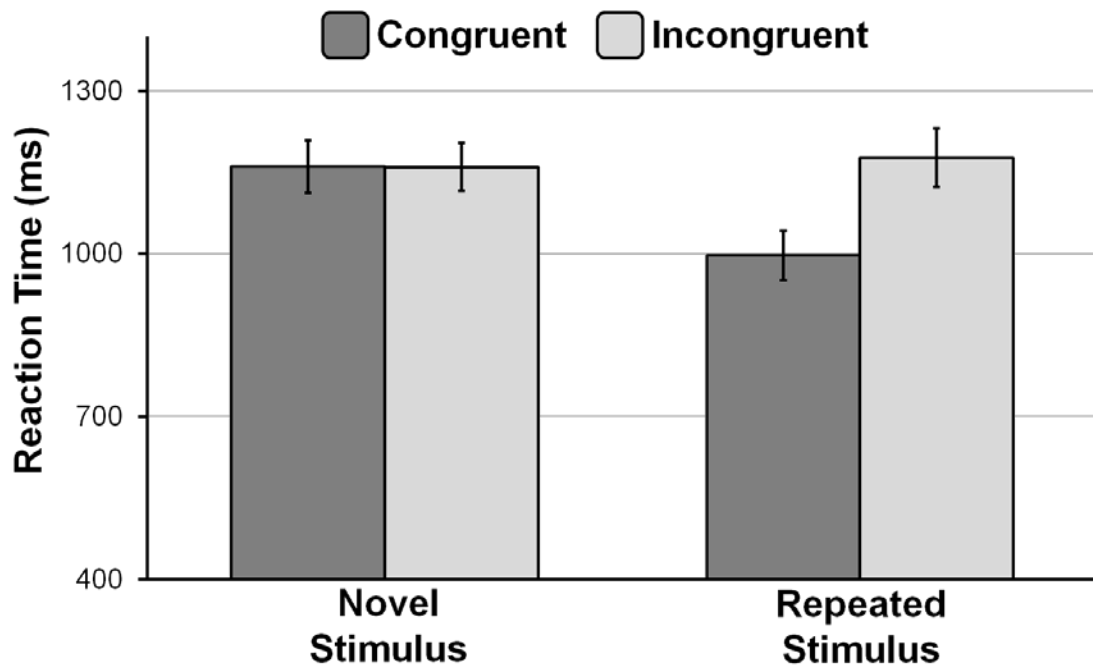
Figure 5.4. The difference in congruency effects between Novel and Repeated Stimulus conditions is larger when examined using a between subjects design. When only the first condition completed by each participant is considered, participants who completed the Novel Stimulus condition first showed no congruency effect in this condition. Participants who completed the Repeated Stimulus condition first showed large congruency effects.

		Congruent			Incongruent		
		Pure	**Nonswitch**	**Switch**	**Pure**	**Nonswitch**	**Switch**
Novel Stimulus	**Origin**	830 (124)	882 (197)	1357 (256)	821 (114)	904 (169)	1319 (242)
	Size	791 (81)	1010 (146)	1391 (244)	805 (96)	987 (149)	1431 (200)
Repeated Stimulus	**Origin**	643 (164)	774 (171)	1131 (291)	641 (160)	956 (235)	1275 (174)
	Size	596 (61)	746 (125)	1053 (269)	567 (59)	895 (170)	1262 (173)
Spatial	**Meaning**	476 (58)	622 (100)	776 (145)	485 (47)	643 (120)	840 (157)
	Position	310 (36)	527 (77)	741 (142)	308 (42)	550 (85)	848 (147)

Table 5.2. Reaction time means and standard deviations for participants who completed the Novel Stimulus condition first. Times are in milliseconds.

		Congruent			Incongruent		
		Pure	Nonswitch	Switch	Pure	Nonswitch	Switch
Novel Stimulus	**Origin**	793 (109)	860 (57)	1277 (162)	842 (167)	923 (114)	1350 (164)
	Size	850 (141)	963 (128)	1331 (171)	888 (102)	1031 (109)	1382 (185)
Repeated Stimulus	**Origin**	653 (104)	857 (129)	1182 (281)	627 (91)	1022 (187)	1381 (238)
	Size	638 (111)	848 (150)	1100 (207)	618 (87)	986 (149)	1318 (254)
Spatial	**Meaning**	478 (48)	623 (133)	758 (178)	502 (57)	684 (136)	812 (136)
	Position	339 (50)	545 (103)	729 (134)	338 (58)	609 (130)	890 (126)

Table 5.3. Reaction time means and standard deviations for participants who completed the Repeated Stimulus condition first. Times are in milliseconds.

Taken together with the previous experiments, these data suggest that task-switching congruency effects in reaction time appear only after repeated assignment of a particular stimulus to a competing category. When the Novel Stimulus condition was presented first, participants showed no task-switching congruency effects in reaction time in this condition. However, in the Repeated Stimulus condition, participants consistently showed positive congruency effects regardless of when this condition was presented. When a stimulus is presented in the Repeated Stimulus condition, repeated mapping of a single stimulus to multiple categories can lead to automatic activation of those categories and subsequent competition at the level of the category and the response.

The carryover of congruency effects from the Repeated Stimulus condition to subsequently create a positive congruency effect in the Novel Stimulus

condition was unexpected. Both the Novel Stimulus condition and the Repeated Stimulus condition used the same tasks, categories, and responses, but stimuli used in the Repeated Stimulus condition did not appear in the pure or mixed-task runs of the Novel Stimulus condition. Thus, even if congruency effects occur in response to the repeated assignment of a particular stimulus to a category, the interference represented by these congruency effects is not entirely stimulus-specific. One possibility for this finding may be that repeated assignment of a single stimulus to a category leads to automatic activation of that category. In the Repeated Stimulus condition, each stimulus is assigned repeatedly to both possible categories. After a few trials of practice, these categories are both automatically activated by the presence of the stimulus, leading to competition when participants attempt to make a response. The activation of these categories seems to occur automatically, not only in response to presentation of a specific stimulus that has been categorized before, but in response to any stimulus that affords categorization according to the potentially-relevant tasks.

Congruency effects increase after practice for Repeated Stimulus condition.

In Experiment 2, I observed a nonsignificant increase in Nonverbal Control congruency effects from initial practice to the first two mixed-task runs when a small set of stimuli were repeated many times over the course of the experiment. In Experiment 3, I observed no such increase in the Verbal Control condition when stimuli were not repeated. The present experiment allowed for a direct comparison of the effect of stimulus repetition. If the increase in congruency effects between initial practice and the early mixed runs in the Nonverbal Control condition was due to repeated assignment of a stimulus to a category, we would expect that the same increase would exist in the Repeated Stimulus condition, but not in the Novel Stimulus condition.

In the Repeated Stimulus condition, the size of the congruency effect was significantly larger in the first two mixed runs than in the initial practice, $F(1,23) = 5.22$, $p < .05$, (Figure 5.5) with 19 out of 24 participants showing larger

congruency effects in the mixed runs. In the Novel Stimulus condition, the size of the congruency effect did not increase ($F(1,23) = .01$, $p = .94$; Figure 5.6). The pattern of increasing congruency effects from initial practice to the first two mixed runs was present in the Repeated Stimulus condition regardless of the order of presentation of the conditions (Novel first: -116 ms in initial practice vs. 161 ms in the first two mixed runs; Repeated first: 53 ms in initial practice vs. 156 ms in the first two mixed runs). The increase in congruency effects only in the Repeated Stimulus condition supports the idea that congruency effects appear after very little experience assigning a specific stimulus to a category in the mixed-task context.
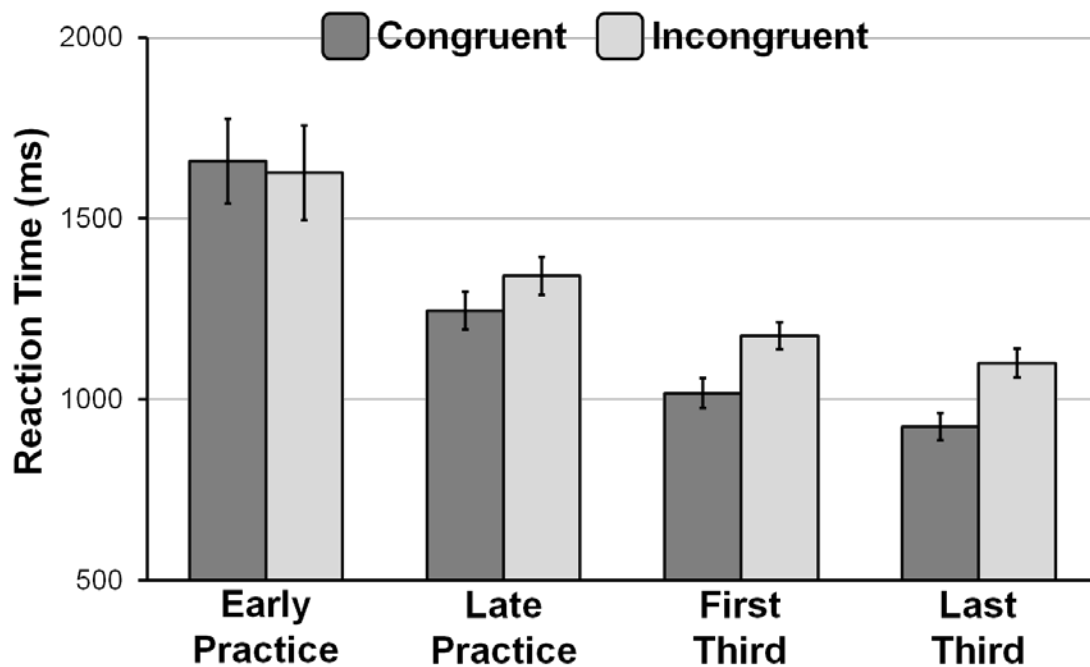
Figure 5.5. Congruency effects in the Repeated Stimulus condition increase over time. Early practice trials are the first 16 trials, in which stimuli are assigned to categories in the mixed-task context and are self-paced with no time limit. Late practice trials are the first set of 16 timed practice trials. First third trials are from the first two mixed-task runs. Last third trials are from the last two mixed-task runs.
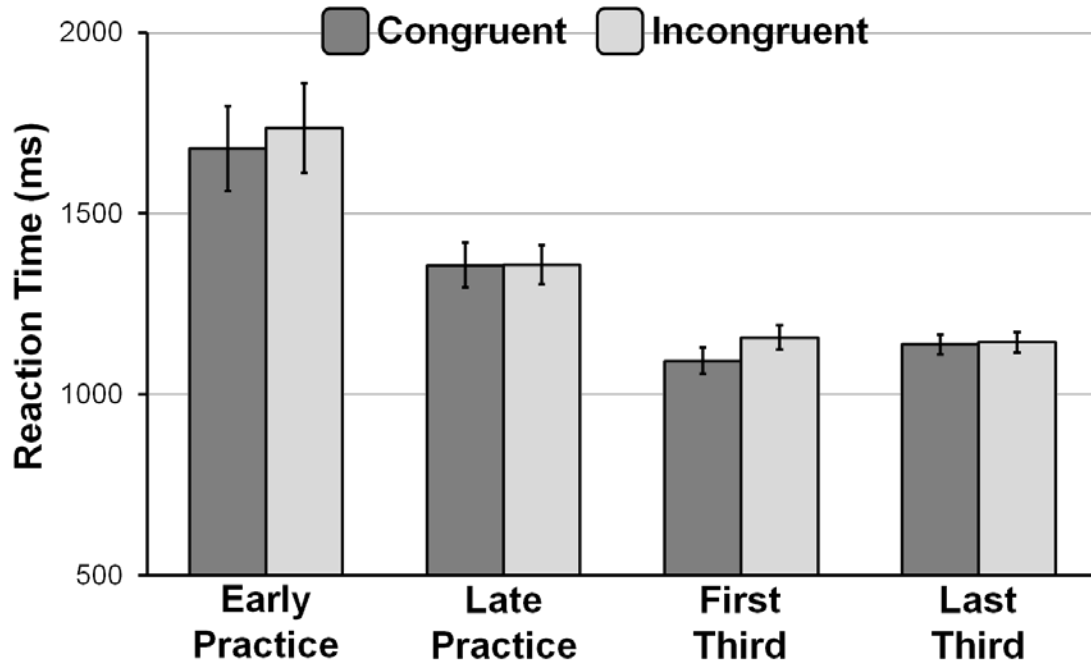
Figure 5.6. Congruency effects in the Novel Stimulus condition do not increase over time. Early practice trials are the first 16 trials, in which stimuli are assigned to categories in the mixed-task context and are self-paced with no time limit. Late practice trials are the first set of 16 timed practice trials. First third trials are from the first two mixed-task runs. Last third trials are from the last two mixed-task runs.

Asymmetry in switch costs and congruency effects.

As in previous experiments, there was a significant task-based asymmetry in switch costs for the Spatial condition, $F(1, 23) = 20.45$, $p < .001$, because switch costs were larger for switching to the dominant position task. There was no significant Switch x Task interaction for either the Repeated Stimulus, $F(1, 23) = .62$, $p = .44$, or the Novel Stimulus condition, $F(1, 23) = 2.45$, $p = .13$.

In Experiment 3, I showed that the Switch x Congruency interaction differed by task in the Spatial condition but not in the Novel Stimulus condition used here. In the present experiment, I replicated those results (Figure 5.7). The Congruency x Switch x Task interaction was significant for the Spatial condition, $F(1, 23) = 5.76$, $p < .05$. The difference between congruency effects on nonswitch and switch trials was larger for the dominant position task. The Switch x Congruency effect was significant for the position task, $F(1, 23) = 20.62$, $p < .001$, but not for the meaning task, $F(1, 23) = .57$, $p = .46$. The Congruency x

Switch x Task interaction was not significant for the Novel Stimulus condition, $F(1, 23) = .63$, $p = .44$. The Congruency x Switch interaction was not significant for either task (origin: $F(1, 23) = .46$, $p = .51$, size: $F(1, 23) = .25$, $p = .62$). The Congruency x Switch x Task interaction was also not significant for the Repeated Stimulus condition, $F(1, 23) = 1.72$, $p = .20$, as the Congruency x Switch interaction did not reach significance for either task (origin: $F(1, 23) = .00$, $p = .97$, size: $F(1, 23) = 3.76$, $p = .07$). This pattern across conditions is consistent for both participants who completed the Novel Stimulus condition first (Table 5.2) and those who completed the Repeated Stimulus condition first (Table 5.3).
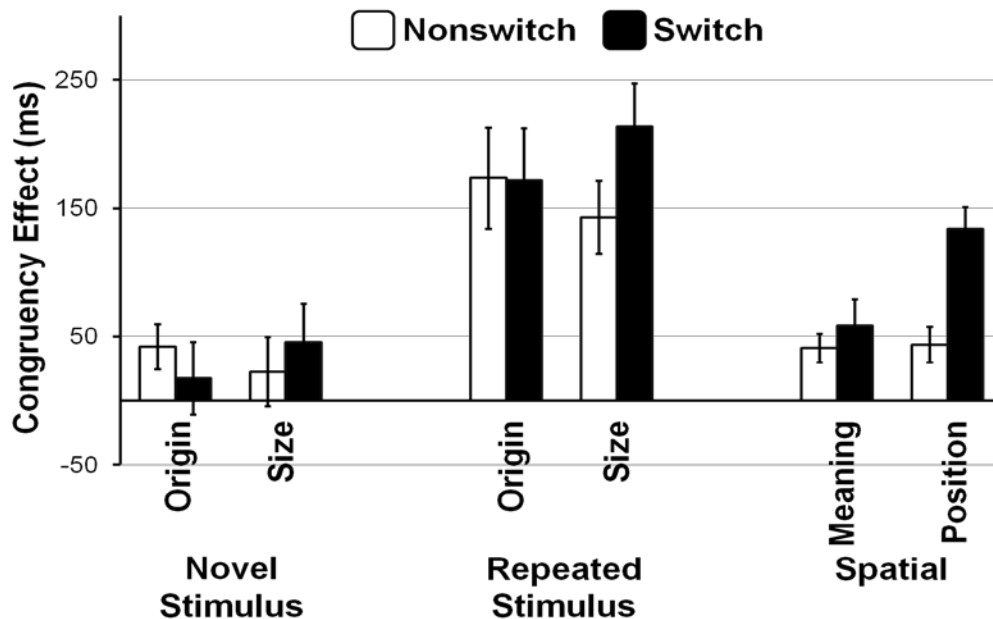
Figure 5.7. The switch difference in congruency effects is larger for the dominant task only in the Stroop-like condition.

Discussion

Previous experiments in this dissertation suggested that task-switching congruency effects are larger in the presence of Stroop-like interference. The present experiment showed that large congruency effects can also be generated by strengthening stimulus–to-category links for a small set of stimuli. In the present experiment, congruency effects were even numerically larger for the Repeated Stimulus condition than for the Spatial condition, which involved

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Stroop-like interference. This effect is counter-intuitive since one rule in the Spatial condition is overlearned before beginning the experiment. Stronger congruency effects in the Repeated Stimulus condition might occur because in this condition, the stimulus-to-category links are strengthened according to both tasks, instead of according to only one task as characterizes the Stroop effect. This would seem reasonable as the congruency effect would potentially occur only for trials corresponding to one task in the Stroop-like condition. However, there are only four potential stimuli in the Spatial condition, just as in the Repeated Stimulus condition. Any within-session increases in congruency in the Repeated Stimulus condition due to recent activation or recent practice might be expected to be the same for the Spatial condition.

I propose instead that salience of the stimulus to be categorized may be the critical difference. In the Repeated Stimulus condition, the individually presented words are salient, concrete, and easy to remember. It is likely that participants attempt to intentionally create explicit category mappings for each stimulus according to each task (e.g., if "scissors" appears, it is a "small" item for the size task and a "manmade" item for the origin task). Though the Spatial condition has the same number of stimuli, representations of all relevant attributes of a single stimulus requires integration of the spatial location and the word meaning (e.g., "Left" on the right side of the screen.) It is likely that participants do not try to make explicit category mappings for each stimulus here. Instead, participants likely think of each stimulus dimension separately (as the word "left" or "right" for the meaning task or as a something on the left or right side for the position task). An argument could be made that participants are simply making explicit stimulus-to-response mappings in the Repeated Stimulus condition. However, direct stimulus-to-response mappings as a source of the congruency effect would not fit with previous work showing that direct stimulus to response mappings in a Simon task are additive with task-switching congruency effects and findings that congruency effects do not appear even after training of direct stimulus-response mappings (Meiran et al, 2005; Meiran & Kessler, 2008).

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While congruency effects in the Repeated Stimulus condition were large and reliable in the mixed-task runs, they were much smaller in the Novel Stimulus condition and negligible if the Novel Stimulus condition was not preceded by the Repeated Stimulus condition. The absence of a congruency effect in the Novel Stimulus condition argues that congruency effects exist only after repeated experience assigning a stimulus to a category. However, the presence of a congruency effect in this condition after exposure to the Repeated Stimulus condition suggests that the congruency effect that is built up with practice in the Repeated Stimulus condition is carried over to the Novel Stimulus condition. Whatever competition is generated in the Repeated Stimulus condition to create a congruency effect must be flexible to exert its influence in a manner that is not entirely stimulus-specific. I have suggested that repeated assignment of a single stimulus to a category leads to activation of that category automatically when a stimulus is presented. Competition occurs between categories and subsequently between responses. The activation of these categories seems to occur automatically in response to presentation of a specific stimulus that has been categorized before and for which a participant has an explicitly-learned categorization. However, these categories are also activated to some extent by any stimulus that affords categorization according to the potentially-relevant tasks.

The present results also support the suggestion of previous experiments that the congruency effect occurs after limited practice assigning a given stimulus to a category. The congruency effect increased from practice to the beginning of the mixed-task runs in the Repeated Stimulus condition. Such an increase did not occur in the Novel Stimulus condition, in which stimuli were not repeated. This is consistent with previous work showing that congruency effects are larger for stimuli that are frequently repeated than for stimuli that are infrequently repeated (Kiesel et al., 2007). Further they demonstrate that the emergence of congruency effects after practice does not rely on sleep-based consolidation of abstract response codes in long-term memory (c.f., Meiran & Kessler, 2008).

Chapter VI

Discussion

Stroop-like and task-switching congruency effects are related

      The experiments presented in this dissertation demonstrate that the presence of Stroop-like interference increases the magnitude of task-switching congruency effects. This fact, which was replicated across stimulus materials in different experiments, argues against previous arguments made by Meiran and Kessler (2008) that Stroop-like congruency effects are fundamentally different from task-switching congruency effects. However, it is consistent with previous neuroimaging studies. Task-switching congruency effects on brain activation are often small and unreliable unless they involve Stroop-like interference. Furthermore, task-switching congruency differences in brain activation overlap with those in Stroop paradigms, with larger activation in anterior cingulate on incongruent trials (Liston et al., 2006; MacDonald et al., 2000). Meiran and Kessler's argument was based on previous work showing that task-switching congruency effects and Simon effects were additive and the assumption that Simon effects and Stroop congruency effects were comparable because both involve stimulus-response associations that exist before entering the laboratory. Though Simon and Stroop effects both involve some pre-existing tendency, it is likely that they are not equivalent for the purposes of comparison to task-switching congruency effects.

      Kornblum (1992, 1994) also argued that Simon effects are fundamentally different from Stroop effects in terms of dimensional overlap. In particular, Simon effects occur only due to direct stimulus-response conflict (the irrelevant stimulus dimension overlaps with the response dimension but the relevant stimulus

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dimension does not) while Stroop effects additionally involve conflict arising from the fact that the stimulus has multiple attributes, each of which affords a response according to the same categorical separation (both the irrelevant stimulus dimension and the relevant stimulus dimension overlap with the response dimension).

In terms of the presented model of task-switching congruency effects, one could say that Stroop-like congruency effects, like task-switching congruency effects, involve a mediated pathway between stimulus and response in which stimuli are categorized according to their attributes before being linked to response. Simon effects do not rely on this category mediation between stimuli and responses. Neuroimaging results support this separation as greater activation in inferior parietal cortex, a region involved in biasing processing in favor of the task-relevant attribute, was found for incongruent relative to congruent trials for a spatial Stroop but not for a comparable Simon task (Liu et al., 2004). This distinction suggests that Simon effects should not interact with task-switching congruency effects but that spatial Stroop effects should interact with task-switching congruency effects. Indeed, Meiran and colleagues found that task-switching congruency effects were additive with Simon effects and I have presented here evidence that task-switching congruency effects interact with Stroop-like effects.

The fact that spatial Stroop effects and Simon effects have been previously distinguished also supports the idea that the interactions between spatial Stroop and task-switching congruency effects demonstrated in the experiments here do not contradict the finding of additivity between the task-switching congruency effect and the Simon effect. We can be especially certain that the interaction between the task-switching congruency effects and Stroop effects in the experiments in this dissertation are not due to an interaction between task-switching congruency effects and some Simon component of the Spatial condition, because the interaction occurs when comparing the Control condition in Experiment 1 to the Numerical condition in Experiment 1. Congruency effects were larger in the Numerical condition than in the Control

condition even though there was no Simon-like (or even spatial) component to the Numerical condition and the effects in the Control condition were not exaggerated by response slowing.

Furthermore, we can assume that the interaction between task-switching congruency effects and Stroop-like congruency effects occur somewhere along a category-mediated pathway. In addition to the absence of interaction between Simon and task-switching congruency effects, Meiran and Kessler (2008) demonstrated that task-switching congruency effects did not develop even after several days of practice in situations in which stimuli were mapped directly to responses without an intermediate category, suggesting that task-switching congruency effects necessarily involve this categorical intermediate. Similarly, the Stroop effect appears to involve assignment of stimulus attributes to a category rather than simply a direct mapping between stimulus and response. In addition to the dimensional overlap account described above, there is evidence that smaller Stroop-like effects can occur when there is conflict at the level of the category even if both categories lead to the same response (De Houwer et al, 2003; Van Veen & Carter, 2005). Furthermore, Stroop-like effects exist to some extent even when direct stimulus-response associations would be assumed to be novel (e.g., using the left index finger to indicate "Blue" in a traditional color-word Stroop; Nielsen, 1974).

Congruency effects occur when stimulus-to-category mappings are repeated

Given that task-switching congruency effects and Stroop congruency effects both involve a pathway mediated by categorization of the stimulus according to one of a set of possible attributes and that these effects interact, I examined which stage along this pathway might be the originating point for the task-switching congruency effect. Based on Experiments 1 and 2, in which all conditions involved category-to-response mappings that might be considered pre-existing (i.e., left hand response for "1" and "left"), it seemed that the difference between the Stroop conditions and the Control conditions may be

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largely related to strength of the association between stimulus and category. In the Stroop-like conditions, these stimulus-to-category mappings were pre-existing, while in the Control conditions, they were likely novel at the beginning of the experiment. To look at this question more specifically, in Experiment 3 and 4, I examined a condition in which each stimulus was assigned to a category only once in the course of the experiment. In this condition, participants showed drastically reduced task-switching congruency effects. In fact, participants showed no task-switching congruency effect in this condition in Experiment 4 if they had not previously encountered the tasks in this condition in the context of repeated stimulus-to-category assignment.

Based on the absence of a congruency effect when stimulus-category associations were not repeated, it seems likely that repeated assignment of a particular stimulus to a category drives the task-switching congruency effect by creating competition between categories. Due to the fact that congruency effects are observed even in the case of bivalent responses (in which both congruent and incongruent stimuli result in competition between semantic categories, but only incongruent stimuli result in additional competition at the level of the response), it is clear that most measured congruency effects reflect competition either at the level of response alone (in the bivalent case) or at the level of the category and the response (in the univalent case).

Meiran and Kessler (2008) previously argued that the congruency effect may occur due to stimulus-category associations; however, Meiran and Kessler argued that these associations exist in long-term memory and that congruency effects are not observed unless these associations have been consolidated into long-term memory after a night's sleep. This claim was based on observations that congruency effects did not appear until the second session in a paradigm in which they had participants repeat stimulus-category assignments. My results contradict the results of Meiran and Kessler on this point as, particularly in Experiments 2 and 4, I have demonstrated significant congruency effects in conditions in which stimulus-to-category associations were novel at the beginning of the experiment. I propose that repeated assignment of a stimulus to a category

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creates stimulus-category associations. These associations activate categories with subsequent presentation of these stimuli, leading to competition between categories and responses.

It would be tempting to conclude that the reactivation of categories is stimulus-specific, and certainly the strength of reactivation may be related to the specific stimulus presented. However, the presence of a task-switching congruency effect in the Novel Stimulus condition when it followed the Repeated Stimulus condition argues that the stimulus-to-category associations developed during the Repeated Stimulus condition allow categories to be reactivated by any stimulus that affords categorization according to the tasks used in the Repeated Stimulus condition. I proposed that salience of the stimulus to be categorized may be the critical difference. In the Repeated Stimulus condition, the individually presented words are salient, concrete, easy to picture, and easy to remember. It is likely that participants attempt to intentionally create explicit category mappings for each stimulus according to each task (e.g., if "scissors" appears, it is a "small" item for the size task and a "manmade" item for the origin task). Though the Spatial condition has the same number of stimuli, representations of all relevant attributes of a single stimulus requires integration of the spatial location and the word meaning (e.g., "Left" on the right side of the screen.) It is likely that participants do not try to make explicit category mappings for each stimulus here. Instead, participants likely think of each stimulus dimension separately (as the word "left" or "right" for the meaning task or as a something on the left or right side for the position task).

The description applied here to the Spatial condition could also apply to the Control condition in Experiment 1. Participants are less likely to make explicit mappings for "circle that is larger on the left side of the screen" than they are for "scissors." The Nonverbal Control condition provides an interesting test of this proposal. In the Nonverbal Control condition in Experiment 2, the same four stimuli are repeatedly categorized resulting in a significant task-switching congruency effect but one that is smaller than that observed in the Repeated Stimulus condition in Experiment 4. The shapes used in the Nonverbal condition

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are unique and integrated as a stimulus. It is possible that some participants make explicit stimulus-to-category links for these four shapes, but that the tendency to do so is not as great as it is in the Repeated Stimulus condition, in which the fact that the four stimuli are unique is much more obvious.

Congruency effects appear after only a few trials of experience categorizing a stimulus

The fact that repeated stimulus-to-category assignment seems to be a crucial factor in development of task-switching congruency effects and the fact that task-switching congruency effects are exaggerated under conditions of overlearning of one task led to questions about the role of within-session experience assigning a stimulus to a category. Contrary to the results reported by Meiran and Kessler (2008), but consistent with the results of Kiesel and colleagues (2007), I found larger congruency effects associated with within-session practice associating a stimulus with a category. However, congruency effects tended not to appear gradually over the course of the mixed runs. Instead, congruency effects appeared at almost full strength after just a few trials of experience categorizing a small set of stimuli. This was true both for the Nonverbal Control condition and for the Repeated Stimulus condition (but was notably not true for the Verbal Control and Novel Stimulus conditions, in which individual stimuli were not repeatedly categorized).

One possible explanation for this finding is that congruency effects result from associative learning. That is, the association between a stimulus and category is learned over practice and leads to automatic reactivation of that category whenever that stimulus (or to a lesser extent, another stimulus with similar properties) appears on a later trial. This effect appears to be long-lasting as it exists even after many trials with non-repeating stimuli when the Novel Stimulus condition follows the Repeated Stimulus condition. The long duration of these effects follows previous work showing that switch costs are greater when one attribute of a stimulus must be responded to when the other attribute of that same stimulus was previously responded to, even if that response occurred

several minutes before (Waszak et al., 2003). It also fits with earlier work on the congruency effect which showed that a patient continued to exhibit the congruency effect even in the absence of switching behavior for hundreds of trials after only a few dozen trials of responding according to both tasks (Yehene et al., 2005).

Meiran and Kessler argued that they failed to find task-switching congruency effects in the first session in a condition with novel stimulus-to-category associations because these associations must exist in long-term memory and require overnight consolidation. Though I do not object to the argument that stimulus-category associations in long term memory lead fundamentally to this effect, the data presented here showing within-session development of the task-switching congruency effect in response to repeated stimulus categorization argue against the need for overnight consolidation. One reason that Meiran and Kessler did not find reliable within-session increases in task-switching congruency effects may be related to the point about explicit stimulus-to-category links described above. Specifically, the stimuli that Meiran and Kessler used may not have been as easy to identify as unique. This may have made creating explicit stimulus-to-category associations more difficult. A stronger possibility is that they failed to find congruency effects in a single session because they presented 80% incongruent trials. Presenting a greater proportion of incongruent trials yields smaller congruency effects in Stroop-like conditions (e.g., Kane and Engle, 2003) and likely would have the same effect here given the similarity between Stroop and task-switching congruency effects.

Congruency effects reflect strength of stimulus-to-category associations which may differ across conditions within an individual

In both the Stroop and task-switching literature, previous authors have failed to find reliable correlations between congruency effects in different paradigms (Yehene & Meiran, 2007; Shilling et al., 2002; Ward et al., 2001). While this lack of correlation could indicate that there is no interference resolution

mechanism common to multiple tasks, the results in the present series of experiments suggest an alternative explanation. Specifically, as shown by the larger congruency effects in conditions with overlearned stimulus-to-category associations, the magnitude of congruency effects is determined by the degree to which a particular category is elicited by a presented stimulus attribute. Strength of the association between a stimulus and a category is related to experience assigning that type of stimulus (and to a certain extent, that exact stimulus) to a category. Since these effects are specific to the types of stimuli and categories presented in a specific paradigm, it is unsurprising that differences in the degree to which a stimulus activates a category in one paradigm versus another within an individual wash out commonality in the strength of the interference resolution mechanism. Correlations between conditions in the experiments presented here provide additional support for this argument. Correlations in reaction time congruency effects across conditions tended to be small whether comparing Stroop-like conditions to each other or to Control conditions. In these cases, the experience that a participant had assigning a certain type of stimulus to a category likely differed substantially across conditions. However, the correlation between reaction time congruency effects in the Novel Stimulus and Repeated Stimulus conditions, which shared stimulus type and tasks, was significant. Similarly, these results would predict that congruency effects in a color-word Stroop with the stimuli "Red," "Brown," and "Green" would be significantly correlated with those effects in a color-word Stroop with the stimuli "Blue," "Yellow," and "Pink," as both paradigms would exploit similar levels of overlearning of stimulus-to-category associations.

Do congruency effects in reaction time and accuracy index different processes?

Meiran and colleagues have proposed that congruency effects can be separated into two distinct components (Meiran, 2000a; Meiran and Kessler, 2008). The first component has to do with accuracy: increases in error rate associated with incongruent trials vs. congruent trials are thought to reflect

incomplete selection of an appropriate task. The second component, an increase in reaction time on incongruent compared to congruent trials, is thought to reflect resolution of interference from activated response category codes in long term memory. By this account, when a stimulus is presented, it triggers the abstract categories corresponding to both tasks. On congruent trials, the response is the same according to the both tasks, facilitating performance. On incongruent trials, the two tasks require different responses. Resolution of this competition requires additional time and may reflect suppression of the currently-irrelevant task set (Arbuthnott, 2005).

Meiran and Kessler's account of congruency effects on accuracy and reaction time in task-switching procedures bears a strong similarity to theoretical accounts of congruency effects in Stroop paradigms. In particular, Kane and Engle (2003) presented a similar explanation for the Stroop effect, dissociating congruency effects in error rate from those in reaction time. They argue that accuracy differences are the result of failure to maintain the appropriate goal whereas reaction time differences are the result of increased time needed to suppress the automatic response even when the correct goal is firmly in mind. The dual-mechanism view of Stroop described by Kane and Engle has obvious parallels with the Meiran and Kessler account of congruency effects in task-switching. Given the results presented here showing similarity between Stroop-like and task-switching congruency effects in reaction time, it seems relevant to consider whether congruency effects in accuracy and reaction time are independent under these conditions.

Some aspects of the data in this dissertation support this proposed distinction between congruency effects in accuracy and those in reaction time. Specifically, congruency effects in accuracy were present in all conditions regardless of the presence of Stroop-like interference or repetition of stimulus-to-category assignment. In all conditions, there are two potentially-relevant tasks. Selecting the wrong goal would lead to an incorrect key press only on incongruent trials. According to the model presented here, this could be considered a failure in the all-or-none goal setting process leading to activation of

the wrong set of rules. Congruency effects in RT, however, were not found in a condition in which stimulus-to-category mappings were novel and not repeated over the course of the mixed runs. Congruency effects in reaction time occur when stimulus-to-category mappings have been repeated leading to automatic associative retrieval of categories when a stimulus is presented that affords categorization. Simultaneous activation of multiple categories results in competition. Resolution of this competition takes time, leading to a congruency effect in reaction time. The strength of competition is related to how strongly potential categories are activated by the presentation of a particular stimulus. One category is preferentially strongly activated in the case of the Stroop-like conditions while both categories may potentially be strongly activated in the case of repeated stimulus-to-category associations within the session, especially for conditions in which the stimulus-to-category associations can be formed explicitly or verbally as in the Repeated Stimulus condition in Experiment 4. Further argument for the distinction between accuracy and reaction time congruency effects comes from the fact that an examination of correlations between congruency effects in accuracy and those in reaction time showed no reliably negative relationships, arguing against a speed-accuracy tradeoff, and relationships were sometimes very close to zero (in the Nonverbal Control, Verbal Control, and Novel Stimulus conditions). See Appendix A for all correlations between RT and accuracy congruency effects.

A few of the data presented here, however, are not entirely consistent with a separation between congruency effects in accuracy and reaction time. Specifically, even though accuracy effects were present in all conditions, congruency effects in accuracy tended to be larger in Stroop-like conditions just like congruency effects in reaction time. Relationships between accuracy and reaction time congruency effects within a condition tended to be positive, but were only occasionally statistically reliable and often heavily influenced by outliers. Though the Nonverbal Control, Verbal Control, and Novel Stimulus conditions show correlations very close to zero, other conditions tended to show r values between .2 and .5, with several conditions showing significant positive

correlations (Control and Numerical in Experiment 1, Spatial in Experiments 3 and 4).

These relationships make it difficult to make an argument that congruency effects in reaction time and those in accuracy are completely independent. An alternative explanation may be that some incorrect responses represent a failure to hold the current goal in mind, leading to differences between congruent and incongruent trials across all conditions. However, other incorrect responses may represent the same response competition that leads to the congruency effect in reaction time. This may occur through a mechanism based on that proposed by Ratcliff and more recently used to describe response selection in Stroop tasks (Ratcliff, 1978; Cohen, Dunbar, and McClelland, 1990).

In such a model, a response is executed when activation at one of the response units exceeds some set threshold. Evidence in support of one response or another is accumulated over the course of each trial according to a random walk model. Reaction time is related to the number of cycles required to activate one of the response units to the threshold level. In the case of congruent trials, activation at one response unit reaches threshold quickly because all evidence accumulates in favor of one correct response leading to accurate responses with quick reaction times. In the case of incongruent trials, however, activation accumulates for both response units (because there is activation of both categories due to past experience). This leads to long reaction time on incongruent trials as it takes more cycles for a single response unit to reach the threshold necessary to execute a response. However, due to the fact that evidence is accumulating in favor of both responses and there is noise in the accumulation of evidence, sometimes the incorrect response unit reaches threshold first, leading to an incorrect response even when the correct task is held in mind. Incorrect responses would be particularly likely in Stroop-like conditions in which there may be substantial evidence for the incorrect response unit due to overlearning. An explanation such as this one, in which some aspect of accuracy is related to successful goal setting, but another aspect is related to

competition at a later stage would explain why congruency effects in accuracy and reaction time exhibit small and often unreliable positive correlations.

Application to task-switching, Stroop, and broader contexts

Though task-switching paradigms almost always include both congruent and incongruent stimuli, investigations of cognitive control processes are usually restricted to examinations of the switch cost (see Monsell, 2003). The present series of experiments suggests that evaluating congruency effects as well as interactions between congruency effects and switch costs may inform our understanding of task switching and of cognitive control processes more broadly. These experiments demonstrated that task-switching congruency effects in reaction time are due to the time needed to resolve interference when the presented stimulus automatically activates a currently-irrelevant category, such that the response derived from that category is in conflict with the response derived from the currently-relevant category.

These data fit nicely with theories of task-switching that posit that part of the residual switch cost is due to associative retrieval based on long-term priming (Allport & Wylie, 2000). Although the relevant task goal may be activated in response to a cue or other task instruction, a residual switch cost exists even when participants are given substantial time to prepare (e.g., Sohn et al., 2000). Presentation of the stimulus leads to activation of multiple mediated stimulus-response pathways (Figure 1.2) for processing, leading to competition which must be resolved. In the case of the residual switch cost, the stimulus activates the category and response associated with the attribute that was relevant on the previous trial. This leads to longer reaction time on switch trials, for which interference must be resolved between the currently-relevant pathway and the one that is automatically activated as a function of being relevant on the last trial. In the case of the congruency effect, reaction time is longer on incongruent trials than congruent trials because of time needed to resolve competition between the two pathways that are be simultaneously active because the stimulus has previously been categorized according to both potentially-relevant tasks. In other

words, both the residual switch cost and the reaction time congruency effect likely arise from competition between the currently-relevant pathway and a previously-relevant pathway. How strongly a stimulus attribute activates a corresponding pathway depends both on how often that attribute has been relevant (leading to congruency effects) and how recently that attribute has been relevant (leading to switch costs).

The set of experiments presented here also provides support for descriptions of the Stroop effect that involve conflict at the level of encoding the stimulus according to one attribute rather than the other, rather than focusing only on competition at the response-output stage. This "stimulus-stimulus" conflict has been suggested as a critical component of the Stroop effect by several previous authors (e.g., Kornblum, 1992; De Houwer, 2003; Liu et al., 2004, Van Veen & Carter, 2005). In the present experiments, Stroop-like congruency effects interacted with task-switching congruency effects, suggesting a similar process. These findings, along with Meiran and Kessler's (2008) evidence that task-switching congruency effects can arise from practice when the condition allows for creation of abstract categories, but not when stimulus-response associations are direct, suggest that Stroop-like congruency effects also involve conflict arising at the stage of encoding the stimulus according to one attribute (e.g., ink color) rather than the other (e.g., word meaning).

Beyond informing the task-switching and Stroop literatures, these experiments also provide a bridge between the two topics. While both task-switching and Stroop are common paradigms for the study of cognitive control processes, there is little effort made to relate the two beyond a general concept of conflict resolution. The findings presented here demonstrate that task-switching and Stroop may be fundamentally the same in that both paradigms allow for two simultaneously-active mediated pathways that connect stimuli to responses. In task-switching, both pathways are active due to task instructions, while in Stroop one pathway is instructed and the other is implicit based on the overlearned tendency to respond based on the dominant attribute. Resolution of competition between these pathways takes time, leading to the time costs

associated with incongruent and switch trials. In other words, the primary difference between task-switching and Stroop is the source of irrelevant-category activation, not the mechanism needed to resolve it.

This deep similarity between task-switching and Stroop paradigms may inform future work, particularly on the topic of training interference resolution (e.g., Persson & Reuter-Lorenz, 2008). The task-switching congruency effect with repeated (but not Stroop-like) stimuli may be particularly well-suited as an outcome measure. Unlike the effects in many other paradigms, the task-switching congruency effect with repeated stimuli appears to increase rather than decrease with practice. Thus, any decreases in the size of this effect between pre- and post-tests would likely be due to improvements in the efficacy of the interference resolution process and not to practice with the paradigm.

The experiments presented here may also tell us something about how we process information in the real world. Perhaps the most powerful finding in the present experiments is that stimulus-driven associations can build up over only a few trials (as in the Repeated Stimulus condition) and that these associations can have powerful effects on behavior even in the artificial laboratory environment. Moreover, once those associations are well-learned, they can generalize to similar stimuli which have never been presented before (as when the Novel Stimulus condition followed the Repeated Stimulus condition). In the real-world context, this may explain why saying "just this once" may lead to unintended, long-term behavioral consequences. For example, allowing your toddler to sleep in your bedroom after one nightmare may lead your toddler to categorize your bed as a place for sleeping and quickly lead to a pattern of him sleeping in your room even when it is not contextually appropriate (e.g., when he has not had a nightmare). Though these experiments add to the existing literature and apply to broader contexts, further experiments could clarify the mechanism underlying task-switching congruency effects.

Future Directions

The experiments presented here provide evidence for the idea that task-switching congruency effects and Stroop-like congruency effects arise from the same type of competition due to automatic activation of a category by the presentation of a stimulus. However, future experiments may address a few additional issues. In the current series of experiments, the cue informing participants of the currently-relevant task was embedded in the stimulus. Given the large amount of attention paid in the task-switching literature to the preparation interval (See Monsell, 2003 for a review), it would be useful for future experiments to separate the cue from the imperative stimulus in order to determine how congruency effects are related to the residual switch cost specifically. This would be particularly useful for addressing the question of whether accuracy and reaction time congruency effects index different processes. If congruency effects in accuracy are largely about failure to shift to the appropriate goal, one would expect that congruency effects in accuracy might be related to length of the preparation interval, while differential congruency effects in reaction time might be related to the residual switch cost.

Another area that should be addressed in future experiments is the addition of a neutral trial type. Congruency effects in my experiments, as well as those in most existing task-switching literature are determined by directly comparing incongruent to congruent trials. This prevents any discussion of the benefit of congruency versus the cost of incongruency, though it is difficult to assess benefits and costs even with a neutral condition (Jonides & Mack, 1984). MacLeod has argued for inclusion of a neutral condition in Stroop comparisons, which may also be appropriate here (MacLeod, 1991).

Based on the findings here regarding the appearance of the congruency effect after only a few trials, future work should also better equate conditions in the practice trials to those in the mixed-task runs for a cleaner comparison of when these effects occur and whether they require previous assignment of a particular stimulus to a competing category or whether assignment of any stimulus to a competing category is sufficient. Previous work by Kiesel and

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colleagues (2007) suggested that congruency effects are larger when stimuli are frequently assigned to a competing category. However, this work did not address how quickly congruency effects can arise.

To relate more directly to real-world situations, future experiments should also consider how congruency effects are modified by the availability of more than two response options. To the best of my knowledge, no examination of response congruency effects in task switching has addressed this possibility. In many real-world situations, a stimulus (e.g., a computer) has more than two potential responses. It is not clear whether congruency effects might be smaller in cases with more available response options because competition from any one alternative would not be as strong or larger because there would be more alternatives competing for the final response.

Appendix A

Correlations between accuracy and reaction time

Reaction time congruency effects are presented in the main text as they are more sensitive and more often studied than accuracy congruency effects. To ensure that reaction time effects were representative of overall performance, correlations were computed between accuracy and reaction time congruency effects in the mixed runs. There were no significant negative correlations, suggesting no speed-accuracy tradeoff in the effects of interest.

Experiment 1
Control RT & Accuracy congruency effects: $r(46) = .37$, $p < .05$
Spatial RT & Accuracy congruency effects: $r(46) = .27$, $p = .07$
Numerical RT & Accuracy congruency effects: $r(46) = .33$, $p < .05$

Experiment 2
Nonverbal Control RT & Accuracy congruency effects: $r(22) = -.06$, $p = .79$
Nonverbal Spatial RT & Accuracy congruency effects: $r(22) = .22$, $p = .31$

Experiment 3
Verbal Control RT & Accuracy congruency effects: $r(22) = -.17$, $p = .42$
Spatial RT & Accuracy congruency effects: $r(22) = .44$, $p < .05$

Experiment 4

Novel Stimulus RT & Accuracy congruency effects: $r(22) = -.09$, $p = .68$

Repeated Stimulus RT & Accuracy congruency effects: $r(22) = .31$, $p = .15$

Spatial RT & Accuracy congruency effects: $r(22) = .49$, $p < .05$

Appendix B

Raw Accuracy

Congruency effects in accuracy were not reliably negatively correlated with reaction time effects, suggesting no speed-accuracy tradeoff. Accuracy results for the primary comparisons in each chapter are presented here for comparison.

Experiment 1

Means and SDs for each condition (in percent correct)

		Congruent			Incongruent		
		Pure	Nonswitch	Switch	Pure	Nonswitch	Switch
Control	**Shape**	95.9	98.7	99.6	98.6	94.4	87.4
		(5.3)	(3.0)	(1.6)	(3.2)	(6.7)	(12.5)
	Size	99.3	99.6	99.3	99.5	96.8	94.9
		(2.0)	(1.6)	(2.0)	(1.8)	(4.5)	(5.8)
Spatial	**Meaning**	98.9	99.4	98.3	97.8	94.5	92.4
		(2.5)	(2.1)	(3.9)	(3.8)	(6.2)	(7.3)
	Position	100.0	99.3	99.5	99.4	90.8	80.5
		(0.0)	(2.1)	(2.2)	(1.9)	(10.8)	(12.7)
Numerical	**Count**	99.3	99.0	99.1	92.5	85.4	83.0
		(2.4)	(2.6)	(2.9)	(6.5)	(12.2)	(13.6)
	Identity	99.6	98.4	98.1	95.7	90.9	79.7
		(1.5)	(3.5)	(4.3)	(11.8)	(8.2)	(11.7)

Single-task results

Control condition

     Task: $F(1,47) = 18.26$, $p < .001$

     Congruency: $F(1,47) = 9.52$, $p < .005$

     Congruency x Task: $F(1,47) = 8.16$, $p < .01$

Spatial condition

     Task: $F(1,47) = 14.91$, $p < .001$

     Congruency: $F(1,47) = 6.36$, $p < .05$

     Congruency x Task: $F(1,47) = . 60$, $p = .44$

Numerical condition

Task: $F(1,47) = 3.61$, $p = .06$

     Congruency: $F(1,47) = 25.23$, $p < .001$

     Congruency x Task: $F(1,47) = 2.28$, $p < .14$

Mixed-task results

Condition x Congruency x Switch: $F(2,94) = .74$, $p = .48$

     Control Congruency x Switch: $F(1,47) = 28.35$, $p < .001$

     Spatial Congruency x Switch: $F(1,47) = 22.81$, $p < .001$

     Numerical Congruency x Switch: $F(1,47) = 24.58$, $p < .001$

Condition x Congruency: $F(2,94) = 35.98$, $p < .001$

     Control Congruency: $F(1,47) = 62.67$, $p < .001$

     Spatial Congruency: $F(1,47) = 135.35$, $p < .001$

     Numerical Congruency: $F(1,47) = 161.43$, $p < .001$

Correlations between congruency effects

     Control & Spatial: $r(46) = .47$, $p < .005$

     Control & Numerical: $r(46) = .57$, $p < .001$

     Spatial & Numerical: $r(46) = .54$, $p < .001$

Congruency effects in Control over time

Means and SDs (in percent correct)

	1st Half	2nd Half
Congruent	98.9 (2.3)	99.6 (1.4)
Incongruent	93.0 (6.1)	93.5 (6.0)

Time x Congruency: $F(1,47) = .02$, $p = .89$

Asymmetry in switch costs & congruency interactions

Asymmetry in switch costs

Control Switch x Task: $F(1,47) = 4.33$, $p < .05$

Spatial Switch x Task: $F(1,47) = 7.99$, $p < .01$

Numerical Switch x Task: $F(1,47) = 9.55$, $p < .005$

Asymmetry in Switch x Congruency interaction

Control Congruency x Switch x Task: $F(1,47) = 9.16$, $p < .005$

Spatial Congruency x Switch x Task: $F(1,47) = 12.70$, $p < .005$

Numerical Congruency x Switch x Task: $F(1,47) = 6.94$, $p < .05$

Experiment 2

Means and SDs for each condition (in percent correct)

		Congruent			Incongruent		
		Pure	**Nonswitch**	**Switch**	**Pure**	**Nonswitch**	**Switch**
Nonverbal Control	**More**	98.1 (3.1)	99.4 (1.5)	98.9 (2.0)	100.0 (0.0)	96.4 (3.3)	92.9 (9.2)
	Taller	98.4 (3.4)	99.2 (1.7)	99.3 (1.7)	98.4 (3.5)	93.6 (7.4)	89.0 (9.2)
Nonverbal Spatial	**Pointing**	98.6 (2.7)	100.0 (0.0)	99.8 (0.9)	97.1 (5.0)	96.1 (4.5)	94.4 (5.4)
	Position	99.2 (2.2)	99.5 (1.5)	98.9 (1.9)	99.7 (1.4)	93.4 (6.4)	83.4 (15.6)

Single-task results

Nonverbal Control

      Task: $F(1,23) = 1.22$, $p = .28$

      Congruency: $F(1,23) = 1.95$, $p = .18$

      Congruency x Task: $F(1,23) = 2.86$, $p = .11$

Nonverbal Spatial

      Task: $F(1,23) = 8.32$, $p < .01$

      Congruency: $F(1,23) = .50$, $p = .48$

      Congruency x Task: $F(1,23) = 2.81$, $p = .11$

Mixed-task results

Condition x Congruency x Switch: $F(1,23) = .72$, $p = .40$

      Nonverbal Control Congruency x Switch: $F(1,23) = 5.89$, $p < .05$

      Nonverbal Spatial Congruency x Switch: $F(1,23) = 12.62$, $p < .005$

Condition x Congruency: $F(1,23) = 1.33$, $p = .26$

      Nonverbal Control Congruency: $F(1,23) = 40.97$, $p < .001$

      Nonverbal Spatial condition Congruency: $F(1,23) = 54.88$, $p < .001$

Nonverbal Spatial dominance & congruency correlation: $r(22) = .00$, $p = .99$

Correlation between congruency effects

      Nonverbal Control & Nonverbal Spatial: $r(22) = .20$, $p = .36$

Congruency effects in Nonverbal Control over time

Means and SDs (in percent correct)

	Early Practice	Late Practice	1st Third	Last Third
Congruent	99.5	99.5	99.7	98.5
	(2.4)	(2.4)	(0.9)	(2.1)
Incongruent	93.0	94.8	92.6	93.4
	(7.1)	(9.6)	(6.4)	(5.5)

Comparison of 1st third & last third of mixed runs

 Time x Congruency: $F(1,23) = 1.85$, $p = .19$

Comparison of early practice & 1st third of mixed runs

 Time x Congruency: $F(1,23) = .13$, $p = .72$

Asymmetry in switch costs & congruency interactions

Asymmetry in switch costs

 Nonverbal Control Switch x Task: $F(1,23) = .03$, $p = .87$

 Nonverbal Spatial Switch x Task: $F(1,23) = 4.96$, $p < .05$

Asymmetry in Switch x Congruency interaction

 Nonverbal Control Congruency x Switch x Task: $F(1,23) = .72$, $p = .41$

 Nonverbal Spatial Congruency x Switch x Task: $F(1,23) = 4.91$, $p < .05$

Experiment 3

Means and SDs for each condition (in percent correct)

		Congruent			Incongruent		
		Pure	**Nonswitch**	**Switch**	**Pure**	**Nonswitch**	**Switch**
Verbal Control	**Origin**	93.7 (5.9)	94.3 (5.5)	94.3 5.5%	96.6% 5.7%	93.0% 14.0%	85.9% 13.0%
	Size	97.4 (3.9)	91.6 (5.3)	81.5% 8.8%	89.6% 8.9%	86.1% 12.0%	75.2% 12.4%
Spatial	**Meaning**	98.1 (3.7)	99.4 (1.5)	97.7% 3.6%	96.5% 6.0%	94.1% 5.5%	94.4% 7.1%
	Position	99.4 (1.9)	99.1 (1.8)	97.4% 3.2%	99.7% 1.3%	95.4% 4.0%	89.0% 8.6%

Single-task results

Verbal Control

> Task: F(1,23) = 2.53, p = .13

> Congruency: F(1,23) = 3.32, p = .08

> Congruency x Task: F(1,23) = 14.79, p < .005

Spatial

> Task: F(1,23) = 7.21, p < .05

> Congruency: F(1,23) = .84, p = .37

> Congruency x Task: F(1,23) = 2.82, p = .11

Mixed-task results

Condition x Congruency x Switch: F(1,23) = .86, p = .36

> Verbal Control Congruency x Switch: F(1,23) = 3.24, p = .09

> Spatial Congruency x Switch: F(1,23) = 1.03, p = .32

Condition x Congruency: F(1,23) = .02, p = .90

> Verbal Control Congruency: F(1,23) = 9.45, p < .01

> Spatial Congruency: F(1,23) = 29.61, p < .001

Correlation between congruency effects

Verbal Control & Spatial: $r(22) = -.03$, $p = .89$

Congruency effects in Verbal Control over time

Means and SDs (in percent correct)

	Early Practice	**Late Practice**	**1st Third**	**Last Third**
Congruent	88.8	89.3	91.3	91.5
	(12.2)	(16.7)	(7.9)	(6.0)
Incongruent	76.3	71.0	88.2	85.8
	(17.6)	(19.9)	(8.4)	(13.5)

Comparison of early practice & 1st third of mixed runs

Time x Congruency: $F(1,23) = 9.12$, $p < .01$

Asymmetry in switch costs & congruency interactions

Asymmetry in switch costs

Verbal Control Switch x Task: $F(1,23) = 10.38$, $p < .005$

Spatial Switch x Task: $F(1,23) = 20.84$, $p < .001$

Asymmetry in Switch x Congruency interaction

Verbal Control Congruency x Switch x Task: $F(1,23) = 3.69$, $p = .07$

Spatial Congruency x Switch x Task: $F(1,23) = 21.63$, $p < .001$

Experiment 4

Means and SDs for each condition (in percent correct)

		Congruent			Incongruent		
		Pure	**Nonswitch**	**Switch**	**Pure**	**Nonswitch**	**Switch**
Novel Stimulus	**Origin**	93.0 (7.8)	94.9 (4.4)	94.4 (5.5)	94.9 (5.8)	95.7 (4.3)	86.4 (11.6)
	Size	94.4 (5.7)	92.9 (5.1)	85.2 (7.5)	96.1 (4.7)	88.2 (11.0)	77.6 (9.6)
Repeated Stimulus	**Origin**	95.7 (7.0)	98.1 (2.9)	97.9 (3.6)	95.9 (5.7)	91.1 (8.1)	82.8 (11.4)
	Size	97.4 (5.6)	98.7 (2.6)	99.2 (2.4)	97.8 (3.2)	95.1 (5.6)	92.5 (6.5)
Spatial	**Meaning**	98.3 (3.0)	99.6 (1.2)	98.1 (4.1)	96.7 (4.5)	95.1 (4.2)	96.6 (4.9)
	Position	100.0 (0.0)	99.8 (0.9)	99.1 (1.8)	100.0 (0.0)	94.9 (6.0)	88.6 (6.8)

Novel first subjects - means and SDs for each condition (in % correct)

		Congruent			Incongruent		
		Pure	**Nonswitch**	**Switch**	**Pure**	**Nonswitch**	**Switch**
Novel Stimulus	**Origin**	93.4 (8.5)	94.3 (5.4)	93.9 (6.2)	92.7 (6.8)	95.7 (2.8)	84.9 (12.0)
	Size	93.2 (6.9)	93.5 (5.6)	85.1 (8.5)	95.6 (5.8)	87.7 (14.2)	77.3 (10.3)
Repeated Stimulus	**Origin**	94.7 (7.2)	98.3 (2.5)	98.9 (1.9)	97.7 (5.4)	89.8 (7.1)	82.2 (12.0)
	Size	96.4 (7.4)	98.9 (1.9)	100.0 (0.0)	97.3 (3.3)	95.5 (4.4)	93.7 (5.8)
Spatial	**Meaning**	97.7 (3.4)	99.6 (1.3)	97.1 (5.0)	95.0 (5.2)	94.5 (4.3)	95.0 (5.4)
	Position	100.0 (0.0)	99.6 (1.3)	99.2 (1.8)	100.0 (0.0)	96.7 (5.6)	89.1 (6.5)

Repeated first subjects - means and SDs for each condition (in % correct)

		Congruent			Incongruent		
		Pure	**Nonswitch**	**Switch**	**Pure**	**Nonswitch**	**Switch**
Novel Stimulus	**Origin**	92.7 (7.4)	95.4 (3.4)	94.9 (4.8)	97.1 (3.5)	95.6 (5.6)	87.9 (11.5)
	Size	95.6 (4.3)	92.3 (4.7)	85.3 (6.8)	96.6 (3.5)	88.7 (7.3)	78.0 (9.2)
Repeated Stimulus	**Origin**	96.6 (6.9)	97.9 (3.3)	96.9 (4.5)	94.2 (5.8)	92.4 (9.1)	83.3 (11.2)
	Size	98.4 (3.0)	98.4 (3.1)	98.3 (3.2)	98.3 (3.0)	94.6 (6.7)	91.4 (7.2)
Spatial	**Meaning**	98.9 (2.5)	99.6 (1.3)	99.2 (2.7)	98.4 (3.0)	95.7 (4.2)	98.2 (3.8)
	Position	100.0 (0.0)	100.0 (0.0)	98.9 (1.9)	100.0 (0.0)	93.1 (6.0)	88.0 (7.2)

Single-task results

Novel Stimulus (all subjects)

    Task: $F(1,23) = 2.53$, $p = .13$

    Congruency: $F(1,23) = 1.95$, $p = .18$

    Congruency x Task: $F(1,23) = .01$, $p = .95$

Repeated Stimulus (all subjects)

    Task: $F(1,23) = 3.45$, $p = .07$

    Congruency: $F(1,23) = .07$, $p = .79$

    Congruency x Task: $F(1,23) = .00$, $p = .95$

Spatial

    Task: $F(1,23) = 16.28$, $p < .005$

    Congruency: $F(1,23) = 3.10$, $p = .09$

    Congruency x Task: $F(1,23) = 3.10$, $p = .09$

Novel Stimulus (Novel first subjects)

     Task: $F(1,11) = 1.52$, $p = .24$

     Congruency: $F(1,11) = .15$, $p = .71$

     Congruency x Task: $F(1,11) = .34$, $p = .57$

Repeated Stimulus (Novel first subjects)

     Task: $F(1,11) = .25$, $p = .62$

     Congruency: $F(1,11) = .99$, $p = .34$

     Congruency x Task: $F(1,11) = .34$, $p = .57$

Novel Stimulus (Repeated first subjects)

     Task: $F(1,11) = .98$, $p = .34$

     Congruency: $F(1,11) = 3.95$, $p = .07$

     Congruency x Task: $F(1,11) = 1.01$, $p = .34$

Repeated Stimulus (Repeated first subjects)

     Task: $F(1,11) = 4.33$, $p = .06$

     Congruency: $F(1,11) = .61$, $p = .45$

     Congruency x Task: $F(1,11) = .78$, $p = .40$

Mixed-task results

Condition x Congruency x Switch: $F(2,46) = 2.55$, $p = .09$

     Novel Stimulus Congruency x Switch: $F(1,23) = 11.79$, $p < .005$

     Repeated Stimulus Congruency x Switch: $F(1,23) = 17.56$, $p < .001$

     Spatial Congruency x Switch: $F(1,23) = .97$, $p = .34$

Condition x Congruency: $F(2,46) = 3.36$, $p < .05$

     Novel Stimulus Congruency (all subjects): $F(1,23) = 15.71$, $p < .005$

     Repeated Stimulus Congruency (all subjects): $F(1,23) = 62.79$, $p < .001$

     Spatial Congruency: $F(1,23) = 65.83$, $p < .001$

Novel Stimulus Congruency (Novel first): $F(1,11) = 6.46$, $p < .05$

Repeated Stimulus Congruency (Novel first): $F(1,11) = 36.98$, $p < .001$

Novel Stimulus Congruency (Repeated first): $F(1,11) = 10.23$, $p < .01$

Repeated Stimulus Congruency (Repeated first): $F(1,11) = 24.99$, $p < .001$

Correlation between congruency effects

Novel Stimulus & Repeated Stimulus: $r(22) = .14$, $p = .51$

Novel Stimulus & Spatial: $r(22) = .12$, $p = .58$

Repeated Stimulus & Spatial: $r(22) = .10$, $p = .63$

Congruency effects in Novel Stimulus over time

Means and SDs (in percent correct)

	Early Practice	Late Practice	1st Third	Last Third
Congruent	90.3 (8.9)	85.2 (16.3)	94.7 (4.5)	87.8 (9.6)
Incongruent	82.0 (12.7)	77.3 (18.2)	93.1 (5.5)	89.5 (6.0)

Comparison of early practice & 1st third of mixed runs

Time x Congruency: $F(1,23) = .20$, $p = .66$

Congruency effects in Repeated Stimulus over time

Means and SDs (in percent correct)

	Early Practice	Late Practice	1st Third	Last Third
Congruent	91.8 (11.9)	92.5 (14.8)	97.8 (3.0)	99.1 (1.6)
Incongruent	82.0 (18.8)	78.9 (20.8)	87.3 (9.7)	90.7 (7.0)

Comparison of early practice & 1st third of mixed runs

Time x Congruency: $F(1,23) = .02$, $p = .87$

Asymmetry in switch costs & congruency interactions

Asymmetry in switch costs

      Novel Stimulus Switch x Task: $F(1,23) = 3.52$, $p = .07$

      Repeated Stimulus Switch x Task: $F(1,23) = 7.58$, $p < .05$

      Spatial Switch x Task: $F(1,23) = 8.31$, $p < .01$

Asymmetry in Switch x Congruency interaction

      Novel Stimulus Congruency x Switch x Task: $F(1,23) = 3.59$, $p = .07$

      Repeated Stimulus Congruency x Switch x Task: $F(1,23) = 3.09$, $p = .09$

      Spatial Congruency x Switch x Task: $F(1,23) = 19.16$, $p < .001$

Appendix C

Log transformed accuracy

Unlike raw reaction time data, it may not be appropriate to examine raw accuracy scores for additivity (Schweickert, 1985). Log-transformed accuracy scores are presented here as a more appropriate comparison.

<u>**Experiment 1**</u>

Means and SDs for each condition

		Congruent			Incongruent		
		Pure	**Nonswitch**	**Switch**	**Pure**	**Nonswitch**	**Switch**
Control	**Shape**	-0.019	-0.006	-0.002	-0.007	-0.026	-0.064
		(0.025)	(0.014)	(0.007)	(0.014)	(0.034)	(0.074)
	Size	-0.003	-0.002	-0.003	-0.002	-0.015	-0.023
		(0.009)	(0.007)	(0.009)	(0.008)	(0.021)	(0.028)
Spatial	**Meaning**	-0.005	-0.003	-0.008	-0.010	-0.026	-0.036
		(0.011)	(0.009)	(0.018)	(0.017)	(0.030)	(0.036)
	Position	0.000	-0.003	-0.003	-0.002	-0.045	-0.100
		(0.000)	(0.009)	(0.010)	(0.008)	(0.059)	(0.072)
Numerical	**Count**	-0.003	-0.005	-0.004	-0.035	-0.074	-0.087
		(0.011)	(0.012)	(0.013)	(0.031)	(0.071)	(0.075)
	Identity	-0.002	-0.007	-0.009	-0.026	-0.043	-0.104
		(0.007)	(0.016)	(0.020)	(0.101)	(0.042)	(0.071)

Single-task results

Control condition

      Task: $F(1,47) = 18.10$, $p < .001$

      Congruency: $F(1,47) = 9.38$, $p < .005$

      Congruency x Task: $F(1,47) = 8.10$, $p < .01$

Spatial condition

      Task: $F(1,47) = 14.83$, $p < .001$

      Congruency: $F(1,47) = 6.37$, $p < .05$

      Congruency x Task: $F(1,47) = .63$, $p = .43$

Numerical condition

      Task: $F(1,47) = .45$, $p = .50$

      Congruency: $F(1,47) = 12.47$, $p < .001$

      Congruency x Task: $F(1,47) = .24$, $p = .63$

Mixed-task results

Condition x Congruency x Switch: $F(2,94) = .87$, $p = .42$

      Control Congruency x Switch: $F(1,47) = 26.98$, $p < .001$

      Spatial Congruency x Switch: $F(1,47) = 22.30$, $p < .001$

      Numerical Congruency x Switch: $F(1,47) = 22.11$, $p < .001$

Condition x Congruency: $F(2,94) = 35.58$, $p < .001$

      Control Congruency: $F(1,47) = 50.51$, $p < .001$

      Spatial Congruency: $F(1,47) = 118.83$, $p < .001$

      Numerical Congruency: $F(1,47) = 134.75$, $p < .001$

Correlations between congruency effects

      Control & Spatial: $r(46) = .46$, $p < .005$

      Control & Numerical: $r(46) = .57$, $p < .001$

      Spatial & Numerical: $r(46) = .51$, $p < .001$

Congruency effects in Control over time

Means and SDs

	1st Half	2nd Half
Congruent	-0.005	-0.002
	(0.010)	(0.006)
Incongruent	-0.033	-0.030
	(0.029)	(0.030)

Time x Congruency: F(1,47) = .01, p = .91

Asymmetry in switch costs & congruency interactions

Asymmetry in switch costs

     Control Switch x Task: F(1,47) = 5.29, p < .05

     Spatial Switch x Task: F(1,47) = 8.47, p < .01

     Numerical Switch x Task: F(1,47) = 8.58, p < .005

Asymmetry in Switch x Congruency interaction

     Control Congruency x Switch x Task: F(1,47) = 9.52, p < .005

     Spatial Congruency x Switch x Task: F(1,47) = 12.43, p < .005

     Numerical Congruency x Switch x Task: F(1,47) = 6.46, p < .05

Experiment 2

Means and SDs for each condition

		Congruent			Incongruent		
		Pure	Nonswitch	Switch	Pure	Nonswitch	Switch
Nonverbal Control	**More**	-0.009	-0.002	-0.005	0.000	-0.016	-0.035
		(0.014)	(0.007)	(0.009)	(0.000)	(0.015)	(0.049)
	Taller	-0.007	-0.003	-0.003	-0.007	-0.030	-0.053
		(0.016)	(0.008)	(0.008)	(0.016)	(0.037)	(0.046)
Nonverbal Spatial	**Pointing**	-0.006	0.000	-0.001	-0.013	-0.018	-0.026
		(0.012)	(0.000)	(0.004)	(0.023)	(0.021)	(0.026)
	Position	-0.004	-0.002	-0.005	-0.001	-0.031	-0.091
		(0.010)	(0.007)	(0.009)	(0.006)	(0.031)	(0.119)

Single-task results

Nonverbal Control

      Task: $F(1,23) = 1.25$, $p = .27$

      Congruency: $F(1,23) = 1.90$, $p = .18$

      Congruency x Task: $F(1,23) = 2.77$, $p = .11$

Nonverbal Spatial

      Task: $F(1,23) = 8.23$, $p < .01$

      Congruency: $F(1,23) = .55$, $p = .47$

      Congruency x Task: $F(1,23) = 2.86$, $p = .10$

Mixed-task results

Condition x Congruency x Switch: $F(1,23) = .97$, $p = .33$

      Nonverbal Control Congruency x Switch: $F(1,23) = 5.42$, $p < .05$

      Nonverbal Spatial Congruency x Switch: $F(1,23) = 7.99$, $p < .05$

Condition x Congruency: $F(1,23) = 1.44$, $p = .24$

      Nonverbal Control Congruency: $F(1,23) = 35.47$, $p < .001$

      Nonverbal Spatial condition Congruency: $F(1,23) = 32.46$, $p < .001$

Nonverbal Spatial dominance & congruency correlation: $r(22) = .05$, $p = .81$

Correlation between congruency effects

      Nonverbal Control & Nonverbal Spatial: $r(22) = .19$, $p = .39$

Congruency effects in Nonverbal Control over time

Means and SDs

	Early Practice	Late Practice	1st Third	Last Third
Congruent	-0.002 (0.011)	-0.002 (0.011)	-0.001 (0.004)	-0.007 (0.009)
Incongruent	-0.033 (0.034)	-0.026 (0.050)	-0.034 (0.031)	-0.031 (0.026)

Comparison of 1st third & last third of mixed runs

Time x Congruency: $F(1,23) = 1.75$, $p = .20$

Comparison of early practice & 1st third of mixed runs

Time x Congruency: $F(1,23) = .11$, $p = .74$

Asymmetry in switch costs & congruency interactions

Asymmetry in switch costs

Nonverbal Control Switch x Task: $F(1,23) = .01$, $p = .91$

Nonverbal Spatial Switch x Task: $F(1,23) = 3.99$, $p = .06$

Asymmetry in Switch x Congruency interaction

Nonverbal Control Congruency x Switch x Task: $F(1,23) = .51$, $p = .48$

Nonverbal Spatial Congruency x Switch x Task: $F(1,23) = 3.96$, $p = .06$

Experiment 3

Means and SDs for each condition

		Congruent			Incongruent		
		Pure	**Nonswitch**	**Switch**	**Pure**	**Nonswitch**	**Switch**
Verbal Control	**Origin**	-0.029 (0.028)	-0.026 (0.027)	-0.026 (0.027)	-0.016 (0.027)	-0.039 (0.097)	-0.072 (0.074)
	Size	-0.012 (0.018)	-0.039 (0.026)	-0.091 (0.050)	-0.050 (0.049)	-0.071 (0.075)	-0.131 (0.085)
Spatial	**Meaning**	-0.009 (0.017)	-0.003 (0.007)	-0.010 (0.016)	-0.016 (0.029)	-0.027 (0.026)	-0.026 (0.034)
	Position	-0.002 (0.008)	-0.004 (0.008)	-0.012 (0.015)	-0.001 (0.006)	-0.021 (0.019)	-0.052 (0.043)

Single-task results

Verbal Control

Task: $F(1,23) = 2.50$, $p = .13$

Congruency: $F(1,23) = 3.40$, $p = .08$

Congruency x Task: $F(1,23) = 12.93$, $p < .005$

Spatial

Task: $F(1,23) = 7.09$, $p < .05$

Congruency: $F(1,23) = .92$, $p = .35$

Congruency x Task: $F(1,23) = 2.86$, $p = .10$

Mixed-task results

Condition x Congruency x Switch: $F(1,23) = .71$, $p = .41$

Verbal Control Congruency x Switch: $F(1,23) = 2.78$, $p = .11$

Spatial Congruency x Switch: $F(1,23) = 1.44$, $p = .24$

Condition x Congruency: $F(1,23) = .34$, $p = .56$

Verbal Control Congruency: $F(1,23) = 6.45$, $p < .02$

Spatial Congruency: $F(1,23) = 28.43$, $p < .001$

Correlation between congruency effects

       Verbal Control & Spatial: $r(22) = -.04$, $p = .87$

Congruency effects in Verbal Control over time

Means and SDs

	Early Practice	Late Practice	1st Third	Last Third
Congruent	-0.056	-0.059	-0.041	-0.040
	(0.068)	(0.100)	(0.041)	(0.029)
Incongruent	-0.133	-0.175	-0.057	-0.075
	(0.127)	(0.180)	(0.045)	(0.101)

Comparison of early practice & 1st third of mixed runs

       Time x Congruency: $F(1,23) = 10.38$, $p < .005$

Asymmetry in switch costs & congruency interactions

Asymmetry in switch costs

       Verbal Control Switch x Task: $F(1,23) = 10.48$, $p < .005$

       Spatial Switch x Task: $F(1,23) = 22.17$, $p < .001$

Asymmetry in Switch x Congruency interaction

       Verbal Control Congruency x Switch x Task: $F(1,23) = 1.60$, $p = .22$

       Spatial Congruency x Switch x Task: $F(1,23) = 21.32$, $p < .001$

Experiment 4

Means and SDs for each condition

		Congruent			Incongruent		
		Pure	**Nonswitch**	**Switch**	**Pure**	**Nonswitch**	**Switch**
Novel Stimulus	**Origin**	-0.033 (0.039)	-0.023 (0.021)	-0.026 (0.026)	-0.023 (0.027)	-0.020 (0.020)	-0.068 (0.063)
	Size	-0.026 (0.027)	-0.032 (0.024)	-0.071 (0.039)	-0.018 (0.022)	-0.059 (0.070)	-0.114 (0.060)
Repeated Stimulus	**Origin**	-0.020 (0.034)	-0.008 (0.013)	-0.010 (0.017)	-0.019 (0.027)	-0.042 (0.043)	-0.087 (0.066)
	Size	-0.012 (0.027)	-0.006 (0.012)	-0.004 (0.011)	-0.010 (0.014)	-0.023 (0.027)	-0.035 (0.032)
Spatial	**Meaning**	-0.008 (0.013)	-0.002 (0.005)	-0.009 (0.019)	-0.015 (0.021)	-0.022 (0.019)	-0.016 (0.023)
	Position	0.000 (0.000)	-0.001 (0.004)	-0.004 (0.008)	0.000 (0.000)	-0.024 (0.029)	-0.054 (0.034)

Novel first subjects - means and SDs for each condition

		Congruent			Incongruent		
		Pure	**Nonswitch**	**Switch**	**Pure**	**Nonswitch**	**Switch**
Novel Stimulus	**Origin**	-0.032 (0.043)	-0.026 (0.026)	-0.028 (0.030)	-0.034 (0.033)	-0.019 (0.013)	-0.075 (0.063)
	Size	-0.032 (0.033)	-0.030 (0.027)	-0.072 (0.044)	-0.020 (0.027)	-0.065 (0.094)	-0.116 (0.069)
Repeated Stimulus	**Origin**	-0.025 (0.035)	-0.007 (0.011)	-0.005 (0.009)	-0.011 (0.025)	-0.048 (0.036)	-0.090 (0.070)
	Size	-0.017 (0.036)	-0.005 (0.009)	0.000 (0.000)	-0.012 (0.015)	-0.020 (0.021)	-0.029 (0.028)
Spatial	**Meaning**	-0.010 (0.015)	-0.002 (0.006)	-0.014 (0.024)	-0.023 (0.024)	-0.025 (0.020)	-0.023 (0.026)
	Position	0.000 (0.000)	-0.002 (0.006)	-0.003 (0.008)	0.000 (0.000)	-0.015 (0.027)	-0.051 (0.032)

Repeated first subjects - means and SDs for each condition

		Congruent			Incongruent		
		Pure	**Nonswitch**	**Switch**	**Pure**	**Nonswitch**	**Switch**
Novel Stimulus	**Origin**	-0.035 (0.037)	-0.021 (0.015)	-0.023 (0.022)	-0.013 (0.016)	-0.020 (0.026)	-0.060 (0.066)
	Size	-0.020 (0.020)	-0.035 (0.023)	-0.070 (0.035)	-0.015 (0.016)	-0.054 (0.038)	-0.111 (0.052)
Repeated Stimulus	**Origin**	-0.016 (0.033)	-0.009 (0.015)	-0.014 (0.021)	-0.027 (0.027)	-0.037 (0.049)	-0.083 (0.065)
	Size	-0.007 (0.013)	-0.007 (0.014)	-0.007 (0.015)	-0.008 (0.014)	-0.025 (0.032)	-0.040 (0.036)
Spatial	**Meaning**	-0.005 (0.011)	-0.002 (0.006)	-0.004 (0.013)	-0.007 (0.013)	-0.020 (0.019)	-0.008 (0.017)
	Position	0.000 (0.000)	0.000 (0.000)	-0.005 (0.008)	0.000 (0.000)	-0.032 (0.029)	-0.057 (0.037)

Single-task results

Novel Stimulus (all subjects)

Task: $F(1,23) = 2.63$, $p = .12$

Congruency: $F(1,23) = 1.93$, $p = .18$

Congruency x Task: $F(1,23) = .01$, $p = .91$

Repeated Stimulus (all subjects)

Task: $F(1,23) = 3.40$, $p = .08$

Congruency: $F(1,23) = .11$, $p = .74$

Congruency x Task: $F(1,23) = .00$, $p = .95$

Spatial

Task: $F(1,23) = 16.06$, $p < .005$

Congruency: $F(1,23) = 3.13$, $p = .09$

Congruency x Task: $F(1,23) = 3.13$, $p = .09$

Novel Stimulus (Novel first subjects)

      Task: $F(1,11) = 1.47$, $p = .25$

      Congruency: $F(1,11) = .17$, $p = .69$

      Congruency x Task: $F(1,11) = .30$, $p = .60$

Repeated Stimulus (Novel first subjects)

      Task: $F(1,11) = .25$, $p = .63$

      Congruency: $F(1,11) = 1.05$, $p = .33$

      Congruency x Task: $F(1,11) = .28$, $p = .61$

Novel Stimulus (Repeated first subjects)

      Task: $F(1,11) = 1.07$, $p = .32$

      Congruency: $F(1,11) = 3.84$, $p = .08$

      Congruency x Task: $F(1,11) = 1.07$, $p = .32$

Repeated Stimulus (Repeated first subjects)

      Task: $F(1,11) = 4.37$, $p = .06$

      Congruency: $F(1,11) = .54$, $p = .48$

      Congruency x Task: $F(1,11) = .68$, $p = .43$

Mixed-task results

Condition x Congruency x Switch: $F(2,46) = 2.59$, $p = .09$

      Novel Stimulus Congruency x Switch: $F(1,23) = 12.33$, $p < .005$

      Repeated Stimulus Congruency x Switch: $F(1,23) = 15.36$, $p < .001$

      Spatial Congruency x Switch: $F(1,23) = 1.14$, $p = .30$

Condition x Congruency: $F(2,46) = 2.27$, $p = .11$

      Novel Stimulus Congruency (all subjects): $F(1,23) = 12.90$, $p < .005$

      Repeated Stimulus Congruency (all subjects): $F(1,23) = 54.12$, $p < .001$

      Spatial Congruency: $F(1,23) = 61.86$, $p < .001$

Novel Stimulus Congruency (Novel first): $F(1,11) = 5.17$, $p < .05$

Repeated Stimulus Congruency (Novel first): $F(1,11) = 31.79$, $p < .001$

Novel Stimulus Congruency (Repeated first): $F(1,11) = 9.50$, $p < .05$

Repeated Stimulus Congruency (Repeated first): $F(1,11) = 21.45$, $p < .001$

Correlation between congruency effects

Novel Stimulus & Repeated Stimulus: $r(22) = .19$, $p = .38$

Novel Stimulus & Spatial: $r(22) = .11$, $p = .62$

Repeated Stimulus & Spatial: $r(22) = .10$, $p = .65$

Congruency effects in Novel Stimulus over time

Means and SDs

	Early Practice	Late Practice	1st Third	Last Third
Congruent	-0.046 (0.044)	-0.081 (0.114)	-0.024 (0.021)	-0.032 (0.026)
Incongruent	-0.091 (0.068)	-0.126 (0.119)	-0.059 (0.053)	-0.049 (0.029)

Comparison of early practice & 1st third of mixed runs

Time x Congruency: $F(1,23) = .34$, $p = .57$

Congruency effects in Repeated Stimulus over time

Means and SDs

	Early Practice	Late Practice	1st Third	Last Third
Congruent	-0.041 (0.063)	-0.041 (0.087)	-0.010 (0.014)	-0.004 (0.007)
Incongruent	-0.102 (0.134)	-0.122 (0.142)	-0.062 (0.053)	-0.044 (0.034)

Comparison of early practice & 1st third of mixed runs

Time x Congruency: $F(1,23) = .16$, $p = .70$

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Asymmetry in switch costs & congruency interactions

Asymmetry in switch costs

      Novel Stimulus Switch x Task: $F(1,23) = 3.12$, $p = .09$

      Repeated Stimulus Switch x Task: $F(1,23) = 7.26$, $p < .05$

      Spatial Switch x Task: $F(1,23) = 7.97$, $p < .05$

Asymmetry in Switch x Congruency interaction

      Novel Stimulus Congruency x Switch x Task: $F(1,23) = 2.99$, $p = .10$

      Repeated Stimulus Congruency x Switch x Task: $F(1,23) = 3.32$, $p = .08$

      Spatial Congruency x Switch x Task: $F(1,23) = 18.32$, $p < .001$

Appendix D

Composite z-scores

Although there were no indications of speed-accuracy tradeoffs in the congruency effects of interest, a composite z-score was created as a combined dependent measure. This composite score was created by taking the z score of each participant's mean reaction time for each cell of interest and adding it to the z-score of that participant's mean error rate for the same cell. Other composite scores, such as bits of information transmitted per second, were considered but were ruled out as potentially inappropriate to the examination of choice reaction time tasks like those presented here (Laming, 2001).

Experiment 1

Means and SDs for each condition

		Congruent			Incongruent		
		Pure	**Nonswitch**	**Switch**	**Pure**	**Nonswitch**	**Switch**
Control	**Shape**	-0.88	-0.45	-0.17	-1.34	-0.01	1.50
		(0.57)	(0.63)	(0.63)	(0.44)	(0.85)	(1.59)
	Size	-1.58	-0.57	0.08	-1.70	-0.17	0.59
		(0.42)	(0.70)	(0.63)	(0.34)	(0.76)	(0.78)
Spatial	**Meaning**	-1.22	-0.50	0.17	-0.99	0.46	1.13
		(0.35)	(0.56)	(0.78)	(0.49)	(1.00)	(0.89)
	Position	-1.97	-0.76	-0.10	-1.83	0.42	2.84
		(0.32)	(0.67)	(0.80)	(0.57)	(1.73)	(1.78)
Numerical	**Count**	-1.34	0.12	0.70	-0.29	2.26	3.10
		(0.47)	(0.79)	(0.72)	(0.94)	(1.64)	(1.90)
	Identity	-1.51	0.04	0.68	-1.04	0.97	3.37
		(0.28)	(0.83)	(0.87)	(1.39)	(1.22)	(1.52)

Single-task results

Control condition

Task: $F(1,47) = 55.36$, $p < .001$

Congruency: $F(1,47) = 25.90$, $p < .001$

Congruency x Task: $F(1,47) = 9.48$, $p < .005$

Spatial condition

Task: $F(1,47) = 114.12$, $p < .001$

Congruency: $F(1,47) = 17.61$, $p < .001$

Congruency x Task: $F(1,47) = .77$, $p = .38$

Numerical condition

Task: $F(1,47) = 11.88$, $p = .005$

Congruency: $F(1,47) = 35.27$, $p < .001$

Congruency x Task: $F(1,47) = 5.85$, $p < .05$

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Mixed-task results

Condition x Congruency x Switch: $F_{(2,94)} = 1.27$, $p = .24$

      Control Congruency x Switch: $F_{(1,47)} = 34.46$, $p < .001$

      Spatial Congruency x Switch: $F_{(1,47)} = 36.47$, $p < .001$

      Numerical Congruency x Switch: $F_{(1,47)} = 35.26$, $p < .001$

Condition x Congruency: $F_{(2,94)} = 51.80$, $p < .001$

      Control Congruency: $F_{(1,47)} = 49.82$, $p < .001$

      Spatial Congruency: $F_{(1,47)} = 173.76$, $p < .001$

      Numerical Congruency: $F_{(1,47)} = 185.82$, $p < .001$

Correlations between congruency effects

      Control & Spatial: $r_{(46)} = .45$, $p < .005$

      Control & Numerical: $r_{(46)} = .54$, $p < .001$

      Spatial & Numerical: $r_{(46)} = .50$, $p < .001$

Congruency effects in Control over time

Means and SDs

	1st Half	2nd Half
Congruent	-0.39	-0.84
	(1.11)	(1.07)
Incongruent	0.89	0.34
	(1.41)	(1.19)

Time x Congruency: $F_{(1,47)} = .33$, $p = .57$

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Asymmetry in switch costs & congruency interactions

Asymmetry in switch costs

      Control Switch x Task: $F(1,47) = 1.81$, $p = .19$

      Spatial Switch x Task: $F(1,47) = 26.28$, $p < .001$

      Numerical Switch x Task: $F(1,47) = 14.77$, $p < .001$

Asymmetry in Switch x Congruency interaction

      Control Congruency x Switch x Task: $F(1,47) = 20.01$, $p < .001$

      Spatial Congruency x Switch x Task: $F(1,47) = 23.80$, $p < .001$

      Numerical Congruency x Switch x Task: $F(1,47) = 10.91$, $p < .005$

Experiment 2

Means and SDs for each condition

		Congruent			Incongruent		
		Pure	**Nonswitch**	**Switch**	**Pure**	**Nonswitch**	**Switch**
Nonverbal Control	**More**	-0.83 (0.65)	-0.26 (0.62)	0.60 (1.01)	-1.25 (0.37)	0.34 (1.04)	1.79 (1.74)
	Taller	-0.94 (0.68)	-0.24 (0.65)	0.45 (0.96)	-1.04 (0.67)	0.84 (1.35)	2.41 (1.66)
Nonverbal Spatial	**Pointing**	-1.02 (0.44)	-0.76 (0.57)	-0.18 (0.88)	-0.49 (1.33)	0.23 (0.80)	1.11 (1.24)
	Position	-1.73 (0.37)	-0.71 (0.65)	0.02 (0.92)	-1.79 (0.38)	0.49 (1.23)	2.96 (2.54)

Single-task results

Nonverbal Control

      Task: $F(1,23) = .17$, $p = .68$

      Congruency: $F(1,23) = 7.16$, $p = .01$

      Congruency x Task: $F(1,23) = 3.09$, $p = .09$

Nonverbal Spatial

      Task: $F(1,23) = 47.01$, $p < .001$

      Congruency: $F(1,23) = 2.90$, $p = .10$

      Congruency x Task: $F(1,23) = 5.13$, $p < .05$

Mixed-task results

Condition x Congruency x Switch: $F(1,23) = .64$, $p = .43$

     Nonverbal Control Congruency x Switch: $F(1,23) = 7.79$, $p < .05$

     Nonverbal Spatial Congruency x Switch: $F(1,23) = 13.50$, $p < .005$

Condition x Congruency: $F(1,23) = 3.47$, $p = .08$

     Nonverbal Control Congruency: $F(1,23) = 55.76$, $p < .001$

     Nonverbal Spatial condition Congruency: $F(1,23) = 83.09$, $p < .001$

Nonverbal Spatial dominance & congruency correlation: $r(22) = .14$, $p = .52$

Correlation between congruency effects

     Nonverbal Control & Nonverbal Spatial: $r(22) = .20$, $p = .35$

Congruency effects in Nonverbal Control over time

Means and SDs

	Early Practice	Late Practice	1st Third	Last Third
Congruent	0.05	-0.49	-0.82	-1.02
	(1.61)	(0.87)	(0.58)	(0.65)
Incongruent	1.10	0.58	0.55	0.04
	(1.45)	(2.00)	(1.30)	(0.92)

Comparison of 1st third & last third of mixed runs

     Time x Congruency: $F(1,23) = 2.08$, $p = .16$

Comparison of early practice & 1st third of mixed runs

     Time x Congruency: $F(1,23) = .80$, $p = .38$

Asymmetry in switch costs & congruency interactions

Asymmetry in switch costs

      Nonverbal Control Switch x Task: $F(1,23) = .02$, $p = .89$

      Nonverbal Spatial Switch x Task: $F(1,23) = 8.17$, $p < .01$

Asymmetry in Switch x Congruency interaction

      Nonverbal Control Congruency x Switch x Task: $F(1,23) = .99$, $p = .33$

      Nonverbal Spatial Congruency x Switch x Task: $F(1,23) = 7.02$, $p < .05$

<u>Experiment 3</u>

Means and SDs for each condition

		Congruent			Incongruent		
		Pure	Nonswitch	Switch	Pure	Nonswitch	Switch
Verbal Control	**Origin**	0.03	0.20	1.31	-0.36	0.28	2.32
		(0.90)	(0.86)	(0.89)	(0.68)	(1.51)	(1.45)
	Size	-0.56	0.70	2.94	0.37	1.32	3.73
		(0.61)	(0.64)	(1.17)	(0.94)	(1.45)	(1.24)
Spatial	**Meaning**	-1.55	-1.20	-0.69	-1.34	-0.46	-0.17
		(0.42)	(0.39)	(0.48)	(0.63)	(0.76)	(0.88)
	Position	-2.13	-1.41	-0.75	-2.17	-0.88	0.47
		(0.22)	(0.40)	(0.44)	(0.20)	(0.70)	(1.01)

Single-task results

Verbal Control

      Task: $F(1,23) = .41$, $p = .53$

      Congruency: $F(1,23) = 3.07$, $p = .09$

      Congruency x Task: $F(1,23) = 19.95$, $p < .001$

Spatial

      Task: $F(1,23) = 51.20$, $p < .001$

      Congruency: $F(1,23) = 1.26$, $p = .27$

      Congruency x Task: $F(1,23) = 3.71$, $p = .07$

Mixed-task results

Condition x Congruency x Switch: $F(1,23) = 1.13$, $p = .30$

      Verbal Control Congruency x Switch: $F(1,23) = 6.09$, $p < .05$

      Spatial Congruency x Switch: $F(1,23) = 2.42$, $p = .13$

Condition x Congruency: $F(1,23) = .34$, $p = .56$

      Verbal Control Congruency: $F(1,23) = 10.99$, $p < .005$

      Spatial Congruency: $F(1,23) = 42.27$, $p < .001$

Correlation between congruency effects

      Verbal Control & Spatial: $r(22) = -.02$, $p = .94$

Congruency effects in Verbal Control over time

Means and SDs

	Early Practice	Late Practice	1st Third	Last Third
Congruent	0.20	-0.39	-0.69	-0.86
	(1.24)	(1.11)	(0.59)	(0.56)
Incongruent	1.78	0.90	-0.51	-0.43
	(2.20)	(1.44)	(0.64)	(0.82)

Comparison of early practice & 1st third of mixed runs

      Time x Congruency: $F(1,23) = 16.27$, $p < .005$

Asymmetry in switch costs & congruency interactions

Asymmetry in switch costs

Verbal Control Switch x Task: $F(1,23) = 7.57$, $p < .05$

Spatial Switch x Task: $F(1,23) = 49.11$, $p < .001$

Asymmetry in Switch x Congruency interaction

Verbal Control Congruency x Switch x Task: $F(1,23) = 3.95$, $p = .07$

Spatial Congruency x Switch x Task: $F(1,23) = 33.43$, $p < .001$

Experiment 4

Means and SDs for each condition

		Congruent			Incongruent		
		Pure	**Nonswitch**	**Switch**	**Pure**	**Nonswitch**	**Switch**
Novel Stimulus	**Origin**	0.07	0.02	1.45	-0.11	0.05	2.55
		(1.13)	(0.87)	(0.84)	(0.93)	(0.65)	(1.58)
	Size	-0.08	0.63	2.78	-0.22	1.32	3.91
		(0.81)	(0.83)	(1.10)	(0.73)	(1.48)	(1.25)
Repeated Stimulus	**Origin**	-0.77	-0.57	0.51	-0.85	0.87	3.00
		(1.17)	(0.69)	(1.13)	(0.86)	(1.29)	(1.84)
	Size	-1.10	-0.70	0.09	-1.22	0.21	1.61
		(0.69)	(0.60)	(0.86)	(0.45)	(0.87)	(1.09)
Spatial	**Meaning**	-1.64	-1.37	-0.73	-1.38	-0.65	-0.35
		(0.41)	(0.36)	(0.89)	(0.52)	(0.67)	(0.61)
	Position	-2.33	-1.66	-0.95	-2.34	-0.88	0.83
		(0.14)	(0.33)	(0.46)	(0.16)	(0.95)	(1.05)

Novel first subjects - means and SDs for each condition

		Congruent			Incongruent		
		Pure	**Nonswitch**	**Switch**	**Pure**	**Nonswitch**	**Switch**
Novel Stimulus	**Origin**	0.08	0.13	1.64	0.14	0.01	2.69
		(1.24)	(1.14)	(1.06)	(1.14)	(0.58)	(1.65)
	Size	-0.01	0.62	2.89	-0.28	1.31	4.03
		(0.93)	(0.99)	(1.15)	(0.85)	(1.98)	(1.41)
Repeated Stimulus	**Origin**	-0.67	-0.73	0.29	-1.06	0.94	2.91
		(1.30)	(0.70)	(0.99)	(0.87)	(1.36)	(1.80)
	Size	-1.04	-0.89	-0.09	-1.23	0.01	1.38
		(0.90)	(0.54)	(0.83)	(0.48)	(0.85)	(0.89)
Spatial	**Meaning**	-1.57	-1.37	-0.56	-1.19	-0.64	-0.10
		(0.42)	(0.25)	(0.96)	(0.63)	(0.73)	(0.65)
	Position	-2.38	-1.66	-0.95	-2.39	-1.21	0.70
		(0.11)	(0.36)	(0.40)	(0.13)	(0.82)	(1.01)

Repeated first subjects - means and SDs for each condition

		Congruent			Incongruent		
		Pure	**Nonswitch**	**Switch**	**Pure**	**Nonswitch**	**Switch**
Novel Stimulus	**Origin**	0.07	-0.09	1.26	-0.37	0.08	2.40
		(1.06)	(0.49)	(0.52)	(0.59)	(0.74)	(1.57)
	Size	-0.15	0.63	2.68	-0.16	1.32	3.79
		(0.71)	(0.68)	(1.09)	(0.62)	(0.83)	(1.11)
Repeated Stimulus	**Origin**	-0.88	-0.42	0.72	-0.65	0.80	3.09
		(1.06)	(0.68)	(1.27)	(0.84)	(1.27)	(1.96)
	Size	-1.16	-0.51	0.27	-1.21	0.41	1.84
		(0.44)	(0.62)	(0.88)	(0.44)	(0.89)	(1.26)
Spatial	**Meaning**	-1.72	-1.36	-0.89	-1.57	-0.67	-0.60
		(0.40)	(0.46)	(0.83)	(0.31)	(0.64)	(0.47)
	Position	-2.29	-1.66	-0.95	-2.29	-0.56	0.97
		(0.15)	(0.32)	(0.54)	(0.18)	(0.98)	(1.12)

Single-task results

Novel Stimulus (all subjects)

       Task: $F(1,23) = 1.16$, $p = .29$

       Congruency: $F(1,23) = .96$, $p = .34$

       Congruency x Task: $F(1,23) = .01$, $p = .92$

Repeated Stimulus (all subjects)

       Task: $F(1,23) = 4.25$, $p = .05$

       Congruency: $F(1,23) = .35$, $p = .56$

       Congruency x Task: $F(1,23) = .03$, $p = .88$

Spatial

       Task: $F(1,23) = 101.97$, $p < .001$

       Congruency: $F(1,23) = 4.25$, $p = .05$

       Congruency x Task: $F(1,23) = 5.16$, $p < .05$

Novel Stimulus (Novel first subjects)

       Task: $F(1,11) = 2.51$, $p = .14$

       Congruency: $F(1,11) = .15$, $p = .71$

       Congruency x Task: $F(1,11) = .19$, $p = .67$

Repeated Stimulus (Novel first subjects)

       Task: $F(1,11) = 1.03$, $p = .33$

       Congruency: $F(1,11) = 1.33$, $p = .27$

       Congruency x Task: $F(1,11) = .17$, $p = .68$

Novel Stimulus (Repeated first subjects)

       Task: $F(1,11) = .00$, $p = .99$

       Congruency: $F(1,11) = 1.23$, $p = .29$

       Congruency x Task: $F(1,11) = .65$, $p = .44$

Repeated Stimulus (Repeated first subjects)

       Task: $F(1,11) = 3.94$, $p = .07$

       Congruency: $F(1,11) = .15$, $p = .71$

       Congruency x Task: $F(1,11) = .54$, $p = .48$

Mixed-task results

Condition x Congruency x Switch: $F(2,46) = 1.39$, $p = .26$

    Novel Stimulus Congruency x Switch: $F(1,23) = 12.73$, $p < .005$

    Repeated Stimulus Congruency x Switch: $F(1,23) = 17.65$, $p < .001$

    Spatial Congruency x Switch: $F(1,23) = 3.22$, $p = .09$

Condition x Congruency: $F(2,46) = 10.46$, $p < .001$

    Novel Stimulus Congruency (all subjects): $F(1,23) = 20.77$, $p < .001$

    Repeated Stimulus Congruency (all subjects): $F(1,23) = 79.63$, $p < .001$

    Spatial Congruency: $F(1,23) = 80.54$, $p < .001$

    Novel Stimulus Congruency (Novel first): $F(1,11) = 6.41$, $p < .05$

    Repeated Stimulus Congruency (Novel first): $F(1,11) = 41.81$, $p < .001$

    Novel Stimulus Congruency (Repeated first): $F(1,11) = 17.98$, $p < .005$

    Repeated Stimulus Congruency (Repeated first): $F(1,11) = 35.05$, $p < .001$

Correlation between congruency effects

    Novel Stimulus & Repeated Stimulus: $r(22) = .13$, $p = .55$

    Novel Stimulus & Spatial: $r(22) = .18$, $p = .41$

    Repeated Stimulus & Spatial: $r(22) = .14$, $p = .51$

Congruency effects in Novel Stimulus over time

Means and SDs

	Early Practice	Late Practice	1st Third	Last Third
Congruent	0.78 (1.62)	0.41 (1.38)	-0.93 (0.59)	-0.70 (0.53)
Incongruent	1.54 (1.78)	1.01 (1.60)	-0.26 (0.72)	-0.42 (0.48)

Comparison of early practice & 1st third of mixed runs

Time x Congruency: $F(1,23) = .09$, $p = 77$.

Congruency effects in Repeated Stimulus over time

Means and SDs

	Early Practice	Late Practice	1st Third	Last Third
Congruent	0.62 (1.73)	-0.40 (1.35)	-1.34 (0.58)	-1.66 (0.45)
Incongruent	1.28 (2.54)	0.85 (1.72)	-0.18 (0.97)	-0.61 (0.80)

Comparison of early practice & 1st third of mixed runs

Time x Congruency: $F(1,23) = 1.90$, $p = .18$

Asymmetry in switch costs & congruency interactions

Asymmetry in switch costs

Novel Stimulus Switch x Task: $F(1,23) = 1.62$, $p = .22$

Repeated Stimulus Switch x Task: $F(1,23) = 6.62$, $p < .05$

Spatial Switch x Task: $F(1,23) = 15.14$, $p < .005$

Asymmetry in Switch x Congruency interaction

Novel Stimulus Congruency x Switch x Task: $F(1,23) = 2.56$, $p = .12$

Repeated Stimulus Congruency x Switch x Task: $F(1,23) = 1.15$, $p = .29$

Spatial Congruency x Switch x Task: $F(1,23) = 24.50$, $p < .005$

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