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The Task Rule Congruency Effect in Task Switching Reflects Activated Long-Term Memory

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Reaction time task rule congruency effects (RT-TRCEs) reflect faster responses to stimuli for which the competing task rules indicate the same correct response than to stimuli indicating conflicting responses. The authors tested the hypothesis that RT-TRCE reflects activated overlearned response category codes in long-term memory (such as *up* or *left*). The results support the hypothesis by showing that (a) RT-TRCE was absent for tasks for which there were no response codes ready beforehand, (b) RT-TRCE was present after these tasks were practiced, and (c) these practice effects were found only if the tasks permitted forming abstract response category codes. The increase in the RT-TRCE with response slowness, found only for familiar tasks, suggests that the abstract response category codes may be verbal or linguistic in these cases. The results are discussed in relation to task-switching theories and prefrontal functions.

Keywords: task switching, working memory, congruency, practice, prefrontal functions

Working memory (WM) and task switching are two core executive functions. Their interrelationships have been studied by means of a variety of approaches. These include examinations of WM load effects on task-switching performance (Baddeley, Chincotta, & Adlam, 2001; Bryck & Mayr, 2005; Emerson & Miyake, 2003), comparing WM span for tasks with WM span of items (Logan, 2004), individual differences studies (e.g., Miyake et al., 2000), and cognitive theorizing (e.g., Logan & Gordon, 2001; Mayr & Kliegl, 2000; Sohn & Anderson, 2001). The present study suggests an as-of-yet unrecognized link between these two functions by focusing on a highly replicable but poorly understood phenomenon from the task-switching literature, the task rule congruency effect (TRCE). In the remainder of the introduction, we review the literature on the TRCE and suggest a WM account for it. The experiments reported in this article provide additional crucial evidence that support our account.

Task Switching and the TRCE

Researchers interested in task control often use the task-switching paradigm. The rationale for this choice is straightforward. Performance in stable conditions without task switching can be done in an "automatic pilot" mode, with little need for active control. This luxury is unavailable when there are frequent task switches. Most of the research has concentrated on the various costs associated with task switching (Fagot, 1994; Jersild, 1927; Monsell & Driver, 2000). However, additional highly replicable effects have also been found, and understanding their basis is likely to shed light on how control is accomplished (cf. Altmann, 2003). In the present work, we concentrate on the TRCE. This effect is among the most reliable found in task-switching experiments, yet relatively little work has been done to unravel its causes.

To the best of our knowledge, Sudevan and Taylor (1987) were the first to demonstrate the TRCE in the context of task switching. The participants in their experiments responded to single digits and switched between two classification tasks: odd–even and high–low (compared against the number 5). They indicated their responses by pressing two keys; for example, high or odd could be indicated by pressing the left key, whereas low or even were indicated by pressing the right key. Consequently, there were *congruent* trials (e.g., 7, which is both high and odd), in which the correct key press was the same in both tasks, and *incongruent* trials (e.g., 3, which is low and odd), in which the correct key press was different in the two tasks. Sudevan and Taylor found that (for the high–low task) congruent trials produced quicker responses than did incongruent trials.

Because the TRCE is a robust phenomenon, understanding it is likely to shed light on how cognitive control operates during task switching. Additionally, there are good reasons to believe that the TRCE reflects prefrontal functioning. Therefore, understanding the reasons for the TRCE may also shed light on the specific functions subserved by this brain region. The most direct evidence for prefrontal involvement comes from studies showing elevated TRCE following prefrontal lesions (Aron, Monsell, Sahakian, & Robbins, 2004; Keele & Rafal, 2000). Konishi, Chikazoe, Jimura, Asari, and Miyashita (2005) as well as Konishi, Jimura, Asari, and Miyashita (2003), who used functional MRI and a rule-generation task, found enhanced prefrontal involvement in incongruent trials

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relative to congruent trials. Furthermore, TRCE has been shown to be elevated in monkeys, in which the prefrontal cortex is proportionally smaller than in humans (Stoet & Snyder, 2003), and in populations in which prefrontal functioning is compromised, such as young children (Cepeda, Kramer, & Gonzalez de Sather, 2001), older adults (Meiran, Gotler, & Perlman, 2001), and children with attention deficits (Cepeda, Cepeda, & Kramer, 2000). An additional motivation to study the TRCE is that its mere presence appears to pose a challenge to some current theories of task switching that assume all-or-none task selection (e.g., Sohn and Anderson, 2001; M. H. Sohn, personal communication, 2004). The reason for this is that it provides prima facie evidence that the currently irrelevant task rule operates in parallel with the relevant rule.

Before proceeding, we would like to make a distinction between the TRCE observed in reaction time (RT), or the RT-TRCE, and the TRCE observed in the proportion of errors (PE), or the PE-TRCE, which we argue are dissociable measures. We will provide evidence for this dissociation in the General Discussion. Below we provide a short review of the literature on RT-TRCE, which is organized according to our empirical generalizations.

RT-TRCE Is Affected by the Current Task Instructions

The RT-TRCE is an automatic effect in the restricted sense of the term *automaticity* as discussed by Tzelgov (1997) because it indicates that there is a process (the processing according to the currently irrelevant rule) that operates irrespective of the current task instruction. In that respect, it resembles the Stroop (1935) effect, indicating slowed color-naming responses to incongruent stimuli, such as the word *red* printed in green. In the case of the Stroop effect, the processing of the irrelevant word information is automatic in the narrow sense. Despite this similarity, the TRCE and the Stroop effect are fundamentally different from one another in that the process that operates regardless of task instructions in the RT-TRCE is at least partly due to recent instructions. For example, in Sudevan and Taylor's (1987) experiments, there was evidence that participants processed parity information while performing the magnitude task. However, what made parity and magnitude compatible or incompatible were the newly instructed category-to-response rules (Schuch & Koch, 2003; e.g., *odd* is indicated by pressing the left key). In contrast, in the Stroop effect, the mapping to responses is not newly instructed but is something that the participants knew before they entered the experiment. Accordingly, the Stroop effect is widely believed to reflect habits and acquired skill-based automaticity (e.g., see MacLeod, 1991, for review).[1] In line with this reasoning, the RT-TRCE is absent or nearly absent in single-task conditions but is usually large and robust when participants switch tasks so that the competing task rule is primed (Fagot, 1994; Meiran, 2000a, 2005). Additionally, Meiran (2005) found that the RT-TRCE was additive with (and hence independent of) the influence of spatial stimulus–response (S-R) compatibility, which, like the Stroop effect, is believed to reflect tendencies that the participants brought into the experiment rather than acquiring during the experiment.

RT-TRCE Is Affected by the Blockwide Preparedness Toward a Task Switch

The argument above is based on, among other things, a comparison of single-task conditions with task switching. One problem with this comparison is that task switching not only requires that participants hold in mind two sets of instructions (as the generalization above suggests). It also involves the priming of the competing task rule in the preceding trials. Yehene, Meiran, and Soroker (2005) found evidence that the RT-TRCE can result from preparedness alone even without the priming of the competitor task in the immediately preceding trials. Specifically, they reported on a neurological patient who stopped switching spontaneously after a few dozen trials, yet showed TRCE in mixed-task conditions that continued for several hundreds of trials and did not show the effect in a subsequent condition in which single-task performance was instructed. Similar results were found in that study among control participants who expected a task switch that never occurred.

TRCE Is Slightly Affected by Recent Task Execution

Although Yehene et al.'s (2005) results show that blockwide preparedness contributes to the TRCE, they do not rule out the contribution of recent task execution. In fact, the prevalent finding is that in mixed-task blocks, the RT-TRCE slightly increases in switch trials relative to trials involving a task repetition (e.g., see Meiran, 2000a, for results and review; see also Koch & Allport, 2006; Meiran, 2005; Yehene & Meiran, in press).

TRCE Does Not Reflect the Influence of Information Held in Limited-Capacity WM

Here we make a distinction between limited-capacity WM and parts of WM that are not (severely) capacity limited. We will elaborate on this point in the next section. Our argument here refers explicitly to those aspects of WM that are believed to be severely limited in their capacity.

We argued above that the RT-TRCE reflects among other things a state of preparedness. It is therefore reasonable to assume that the RT-TRCE would be reduced when participants are told in advance to prepare for a specific task. Providing such advance information presumably enables them to remove the irrelevant instruction set from WM and replace it with the relevant instruction set (Mayr & Kliegl, 2000). Furthermore, successful removal of the irrelevant instruction set from WM should reduce or even eliminate the TRCE.

However, there are two findings that contradict this expectation. First, many task-switching experiments manipulated the task prewarning time. The common finding in these experiments was that prewarning time does not reduce the RT-TRCE (see the early sessions in Sudevan & Taylor, 1987; see also Meiran, 1996, 2000a, 2005; but for exceptions, see Goschke, 2000; Monsell & Mizon, 2006; and the late sessions in Sudevan & Taylor, 1987). Second, Kiesel, Wendt, and Peters (2007) showed that the TRCE is virtu-

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[1] In fact, the reverse Stroop effect (interference from incongruent colors found in the word-reading task) might provide a better analogy to the RT-TRCE because the effect is not normally found when participants perform the word-reading task as a single task. It is found in conditions in which the nonhabitual color-naming task is primed either by practice (Stroop, 1935) or by switching between color naming and word reading (Allport, Styles, & Hsieh, 1994).

ally unaffected by a passive WM load, suggesting that the task expectancies do not reside within limited-capacity WM.

RT-TRCE Is Task Specific

A recent individual differences study by Yehene and Meiran (in press) found that the reliable variance in the RT-TRCE was uncorrelated ($r = .12$, *ns*) across two task-switching paradigms. Similarly, Kiesel, Kunde, and Hoffmann (2007) found evidence that the RT-TRCE reflects the suppression of task-specific representations.

Before presenting our hypothesis concerning the origins of the RT-TRCE, we present the necessary background on activated long-term memory (LTM).

Background on Activated LTM

Cowan's (1988) and Oberauer's (2001, 2002; see also Woltz & Was, 2007) models of WM distinguish between two WM components. The first component involves the currently active LTM representations. This activated LTM is not severely limited in its capacity. A subportion of the activated LTM representations is placed within the focus of attention, which is severely limited in its capacity. There is some debate concerning the type of "activation" involved in activated LTM. Some authors suggest that these are activated representations (Cowan, 1988; Oberauer, 2001, 2005). Other authors suggest that activated LTM involves procedures such as those used in classifying an item (e.g., "dog") into a category (e.g., "animal") (Woltz & Was, 2007).

The most relevant piece of evidence linking the RT-TRCE to activated LTM is the intrusion effect observed by Oberauer (2001). Specifically, in Oberauer's experiments, participants were asked to keep in mind two sets of items and to indicate whether a probe item belonged to a specified target set. The trial began with instructions regarding which set of items was relevant, and the prewarning time between the instructions and the probe was manipulated. It is important to note that there were three probe types: probes that belonged to the relevant set (and required a *yes* response), probes that did not belong to any set (requiring a *no* response), and probes that belonged to the irrelevant set (also requiring a *no* response). Oberauer found that correctly rejecting a probe item took longer if that item belonged to the irrelevant item set than if it did not belong to any set. Furthermore, this intrusion effect was found even with ample prewarning time. Oberauer interpreted the intrusion effect as evidence for activated LTM. Oberauer also manipulated the size of each set of items. The size of the relevant item set affected RT. This was not true for the size of the irrelevant set (when sufficient time was allowed to focus on the relevant set). This last finding was taken as evidence that activated LTM is not severely limited in its capacity. In addition, Woltz and Was (2007) measured how previously held WM information affects category decision times that were performed after variable intervals. The authors showed that recently used LTM structures remained active even for the longest interval used, which was several minutes. Of importance, although their results indicated some decay of activation over the first few seconds, there was no evidence for further decay afterward. Finally, an important additional confirmation that the effect arises from LTM representations comes from a study by Burghardt and Parmentier (2005), who replicated Oberauer's intrusion effect for familiar items (which are presumably associated with LTM representations) but not for unfamiliar items (which are presumably not associated with LTM representations).

Relations Between Activated LTM and the RT-TRCE

The intrusion effect and the RT-TRCE appear similar. In both cases, previously relevant but currently irrelevant information affects performance, the resultant interference is relatively immune to preparation, and the interference seems to be relatively long lasting, up to several minutes. However, one notable difference between these effects seems potentially important. Figure 1 outlines a conceptual analysis of the representations and transformations involved in making the numerical judgments in Sudevan and Taylor's (1987) experiments. In this example, the representation of the numeral *8*, the knowledge that it is an even number and a high (>5) number, and the concepts *odd* and *high* are all in LTM because this is knowledge that the participants had brought with them to the experiment. However, the category-response translation rules, such as "IF high THEN press left" (Schuch & Koch, 2003), are novel and have been introduced during the experiment. These rules determine which condition is congruent and which is incongruent. Moreover, Meiran (1996) demonstrated that the RT-TRCE shows up immediately, even in the first block of the experiment or in very short experiments.

On the basis of the above evidence, one could argue that the RT-TRCE reflects the operation of newly instructed rules (e.g., Cohen-Kdoshay & Meiran, 2007) rather than activated LTM. Demonstrating the LTM involvement in the RT-TRCE would rule out this alternative hypothesis.

A Hypothesis: The RT-TRCE Reflects Activated LTM

Figure 1 has three types of information in LTM: stimulus codes (*8*), response codes (high, even), and the transformations that link the former to the latter. There are two potential processing routes in the figure (see Pashler & Baylis, 1991). The first is a mediated pathway, in which the stimulus code is translated into a response category code prior to being translated into a response code. We

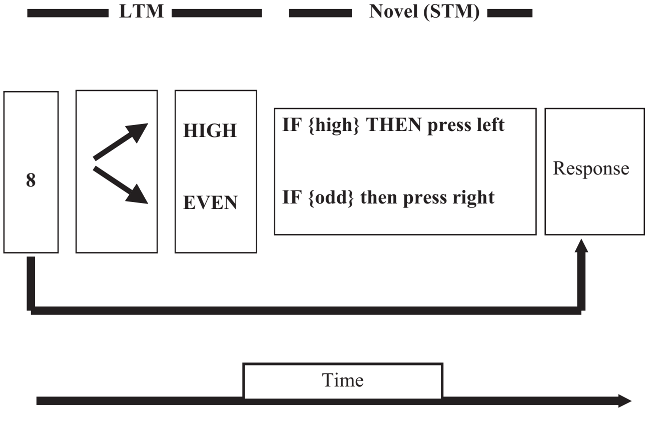

Figure 1. Schematic representation of the hypothesized mediating route and nonmediated route in Sudevan and Taylor's (1987) experiments. LTM = long-term memory; STM = short-term memory.

make no commitment here as to whether the response code is an actual motor program or an abstract spatial code (e.g., Campbell & Proctor, 1993). The other route is direct and does not involve mediation because it links the stimulus directly to the response. Our hypothesis is that the RT-TRCE reflects processing along the mediated route. It reflects either the activation of the abstract irrelevant-response category or the rule relating the stimulus to this irrelevant category. Because we are not committed to any one of these options, we refer to “mediator codes” or “mediators” more generically.

How does the hypothesis explain the results in the literature? To better appreciate our idea, consider switching between an up–down and a right–left task (see Figure 2, control condition; and Figure 3). We suggest that when participants prepare themselves for the task-switch block (or after they perform the first few trials), some or all of the LTM representations that were used to make the classifications become a part of activated LTM. In the case of the spatial task presented in Figure 2, these structures involve the abstract response categories *up*, *down, right,* and *left* or the rules relating the stimuli to these categories. Because these mediator codes are highly accessible, when a target stimulus is presented, both the relevant response category (*up,* in Figure 3) and the irrelevant category (*left,* in Figure 3) become activated. This situation creates the risk that individuals will apply the wrong rule during responding (Ach, 1910/2006; Meiran & Daichman, 2005). To ensure task-appropriate responding, experimenters ask participants to focus their attention on the relevant subset of response categories (*up* and *down* in Figure 3). Still, activated LTM codes that were triggered by the target stimulus (*left*) continue to influence performance. This either facilitates or slows responding depending on the congruency relationships between the relevant response and the irrelevant response. Very similar ideas were proposed in the task-switching literature by Meiran (2000a) and

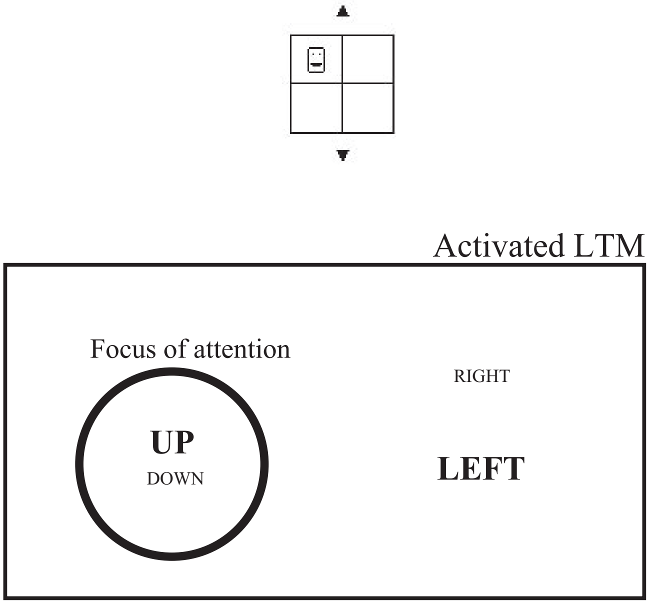

Figure 3. Activated long-term memory (LTM) and the focus of attention in the control condition.

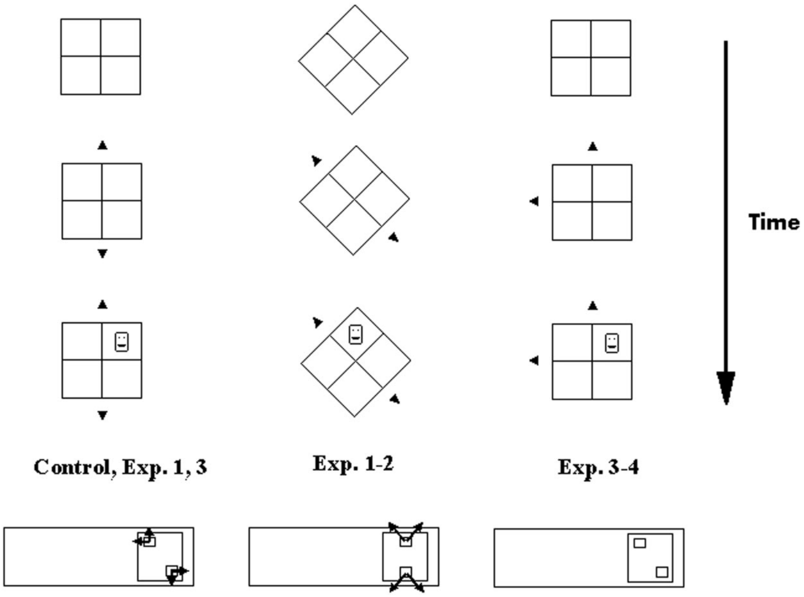

Figure 2. Schematic descriptions of the paradigms used in the present experiments (Exp.). The paradigm used in the control condition required up–down (in the figure) and right–left (not shown) judgments. The paradigm used in the experimental condition in Experiments 1 and 2 required that participants judge whether the target was above (or to the left of) or below (or to the right of) the diagonal running from upper left to lower right (shown). The other task required that participants judge whether the target appeared above (or to the right of) or below (or to the left of) the diagonal running from upper right to lower left (not shown). The paradigm used in the experimental condition of Experiments 3 and 4 required that participants determine the response based on cue–target compounds.

D. W. Schneider and Logan (2005), and in reference to an analogous effect (the backward compatibility effect) in studies by Hommel (1998) and Logan and Gordon (2001).

Our hypothesis accords with the five empirical generalizations listed above. Specifically, we argue that task instructions and possibly the initial task practice activate the relevant codes in LTM, which is why the RT-TRCE reflects task instructions and blockwide preparedness. The slight increase in RT-TRCE in switch trials relative to repeat trials reflects the recent activation of the irrelevant codes. It resembles the slight decay in activated LTM over a few seconds as observed by Woltz and Was (2007). The insensitivity to WM load (Kiesel et al., 2007) reflects the fact that it is the activated LTM that is responsible for the effect in conjunction with the finding that activated LTM is not (severely) limited in its capacity. Finally, the task specificity of the effect accords with the high degree of task specificity recently reported by Woltz and Was (2007) for activated LTM and by the task-specific nature of the response codes.

It is notable that two task-switching theories assume that task preparation involves placement of the relevant task rules in WM and removal of the irrelevant rules from this store (Mayr & Kliegl, 2000; Sohn & Anderson, 2001). The presence of the RT-TRCE seemingly challenges these theories. However, if the effect is due to activated LTM and not to the placement of task rules in limited-capacity WM (the focus of attention), then there is no challenge to meet.

It is interesting to note that this hypothesis accords with a surprising finding by Rubin and Meiran (2005) that the number of tasks for which one prepares in task-switching situations does not affect performance. The reason why this finding may be surprising is that it was widely believed that the task rules are kept within the limited-capacity WM. If so, one would predict that with more tasks, WM load increases and performance should suffer. However, if the rules are kept within a system with a large capacity (activated LTM), the finding makes perfect sense.

The present experiments were aimed at providing support for a core assumption of our hypothesis that the RT-TRCE results from activated LTM codes, which served as mediators. We used a spatial task-switching paradigm (see Figure 2, Control setup, in Meiran, 1996) and introduced manipulations that minimally changed the display, yet made the tasks novel. Because mediator codes of novel tasks are not (an established) part of LTM, we predicted that the RT-TRCE would be eliminated. This part of the study is the task-switch analog of Burghardt and Parmentier's (2005) study on WM, showing that the intrusion effect, which serves as an index for activated LTM, is not found for novel items. We went further and introduced a practice manipulation that was used to establish LTM representations of the novel codes, representations that were predicted to generate a RT-TRCE according to our hypothesis. For reasons that will become clear later, we used two different manipulations to make the tasks novel. To allow for a direct comparison between these manipulations, we ran Experiments 1 and 3 as a single experiment.

Experiment 1

The first manipulation that we used to make the tasks novel involved rotating the display as well as the response key arrangement by 45° (see Figures 2 and 8). In terms of Figure 1, rotation rendered the use of the overlearned codes *up, down, right,* and *left* ineffective and made it essential to form new response categories. Because the response categories were new, the translation of stimuli to response categories was also new.[2] This novel setup was compared against the standard upright setup in which the tasks were familiar: Up–down and right–left and the overlearned response categories could be used as well as the overlearned translation rules between stimuli and responses. An important consideration is that participants could respond correctly in congruent trials even when applying the wrong task rule (Meiran & Daichman, 2005). To ensure that they rarely did so, we used a high proportion of incongruent trials (.75) in all the experiments. The point here is that responding according to the wrong rule in incongruent trials would produce an error. In addition, we strongly emphasized high accuracy in the instructions. Thus, maintaining correct responding in these conditions required that the correct rules be applied in the vast majority of the trials. We predicted that the RT-TRCE would be found in the standard (control) condition but would be absent in the rotated condition.

Method

Participants

Thirty-seven undergraduate students took part in Experiments 1 and 3 in return for partial course credit. There were 12 participants in the control group, 12 participants in the experimental group of Experiment 1, and 13 participants in the experimental group of Experiment 3. Thus, 24 participants (experimental group and control group) took part in this experiment. The students came from Ben-Gurion University of the Negev and from the affiliated Sapir and Achva colleges. All of them reported normal or corrected-to-normal vision. The 37 participants were assigned to the groups and to key arrangement within group (see below) according to the order in which they entered the study, so that the 1st participant was assigned to one group, the 2nd was assigned to another group, and so forth.

Apparatus and Stimuli

The experiment was run on a Pentium III computer with a 14-in. monitor. The software was programmed in E-Prime (W. Schneider, Eschman, & Zuccolotto, 2002).

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[2] One could make the case that although the tasks in the rotated condition were novel, these tasks could be executed with the familiar codes up, down, right, and left. This may be true, but the 45° rotation renders these familiar codes much less useful as compared with the standard upright orientation. The reason is that any such code cannot be uniquely linked to a response. Therefore, participants cannot ensure task-appropriate responding by focusing on a subset of codes. For example, consider the task depicted in Figure 2 (Experiments 1 and 2). This task requires that participants discriminate between up–left and down–right. The other task, not presented in Figure 2, requires discriminating between up–right and down–left. Note that the categorical codes up, down, right, and left feature in both rules. This situation contrasts with that in the control condition, where each set of codes—up and down versus right and left—is uniquely linked to one task rule. Thus, focusing attention on a subgroup of activated codes in WM can ensure task-appropriate responding in the standard upright condition but cannot do so in the rotated condition.

For the control group, the stimuli were identical to those in previous research using the present paradigm. The stimuli were drawn in white on black. We used a 2 × 2 grid that was presented at the screen center and subtended a visual angle of approximately 3.4° (width) × 2.9° (height). The target stimulus was a smiley face that subtended approximately 0.3° (width) × 0.5° (height). The arrow heads subtended approximately 0.3° × 0.3° and were positioned 0.7° from the end of the grid (visual angles are computed on the basis of an assumed 60-cm viewing distance). Of the target stimuli, 75% were incongruent and 25% were congruent (where congruency was defined according to the specific key arrangement). For the rotated condition, the 2 × 2 grid and the arrow heads were rotated by 45°. The smiley-face character was not rotated, however (see Figure 2).

Procedure

The experiment began with verbal instructions, which described the tasks with verbal terms for the responses. The instructions were followed by 20 mixed-task trials serving as a warm-up. They were followed by eight experimental blocks (80 trials each). The experiment lasted about 40 min. Each trial began after the response in the preceding trial.

A trial started with a response–cue interval of 1,000 ms, in which an empty grid was presented. This was followed by the presentation of the instructional cue for a cue–target interval of 0, 100, 300, or 900 ms. Then, the target stimulus was presented until the response was given. The Hebrew word for "error" was presented for 1,000 ms after an error was made. The task and cue–target interval were selected pseudorandomly on each trial, whereas the target was selected pseudorandomly with the constraint of having 75% incongruent trials and 25% congruent trials. Hence, the instructional cue did not indicate the upcoming target location, keypress, or the precise target onset. The response keys were counterbalanced between participants. In the control group, the combinations were either upper left and lower right (the keys *7* and *3* on the keypad) or upper right and lower left (*9* and *1* on the keypad). The keypad was aligned with the center of the screen, and the participants were instructed to respond with their two index fingers. In the experimental group, half of the participants used the keys *8* and *2* on the keypad. The key *8* indicated the directions up–right or up–left, and the key *2* indicated the directions down–right or down–left. The other half of the participants used the keys *6* (up–right or down–right) and *4* (up–left or down–left). These keys form the same spatial arrangement as the response keys in the control group, except for a rotation by 45°. Thus, for the experimental group, both the stimuli and the responses were rotated by 45° relative to those for the control group. Except for these differences, the experimental group received the same conditions as the control group.

Results

RTs that fell outside the 100- to 3,000-ms range (1%) were not analyzed. These trials were analyzed for correctness, however. Error trials or trials that immediately followed an error were analyzed for accuracy only. Alpha levels were set at .05 in all of the analyses. Table 1 summarizes the RT analysis of variance (ANOVA). All of the independent variables except for group were manipulated within participants.

RT

The group effects were the focus of this experiment. The predicted interaction between congruency and group was significant. As seen in Figure 4, there was a significant congruency effect of 84 ms in the control group, $F(1, 22) = 29.75$, $MSE = 11{,}501.95$. However, there was no congruency effect (0 ms) in the experimental group. No other effects involving group reached significance.

It is important to note that we found the usual significant switch and cue–target interval effects and a significant interaction between them. None of these differed significantly among the groups, as indicated by the nonsignificant interactions between

Table 1
Analysis of Variance Tables—Experiment 1

		RT			PE		
Effect	*df*	*F*	*MSE*	*p*	*F*	*MSE*	*p*
Group	1, 22	0.02	735,900.09	.88	1.49	.0884	.24
Cue–target interval (CTI)	3, 66	47.18	8,770.71	<.05	2.68	.0007	.05
Switch	1, 22	55.96	17,014.93	<.05	22.28	.0023	<.05
Congruency	1, 22	15.59	11,501.95	<.05	12.14	.0095	<.05
CTI × Group	3, 66	0.27	8,770.71	.85	1.81	.0007	.15
Switch × Group	1, 22	0.10	17,014.93	.75	0.14	.0023	.71
Congruency × Group	1, 22	14.18	11,501.95	<.05	0.72	.0095	.41
CTI × Switch	3, 66	4.77	4,088.54	<.05	2.31	.0004	.08
CTI × Congruency	3, 66	1.88	3,457.55	.14	4.09	.0005	<.05
Switch × Congruency	1, 22	3.10	6,034.08	.09	31.98	.0010	<.05
CTI × Switch × Group	3, 66	0.15	4,088.54	.93	1.09	.0004	.36
CTI × Congruency × Group	3, 66	1.59	3,457.55	.20	0.73	.0005	.54
Switch × Congruency × Group	1, 22	0.25	6,034.08	.62	0.56	.0010	.46
CTI × Switch × Congruency	3, 66	0.97	3,772.42	.41	3.08	.0006	<.05
4-way interaction	3, 66	0.92	3,772.42	.44	0.72	.0006	.54

Note. PE = proportion of errors.

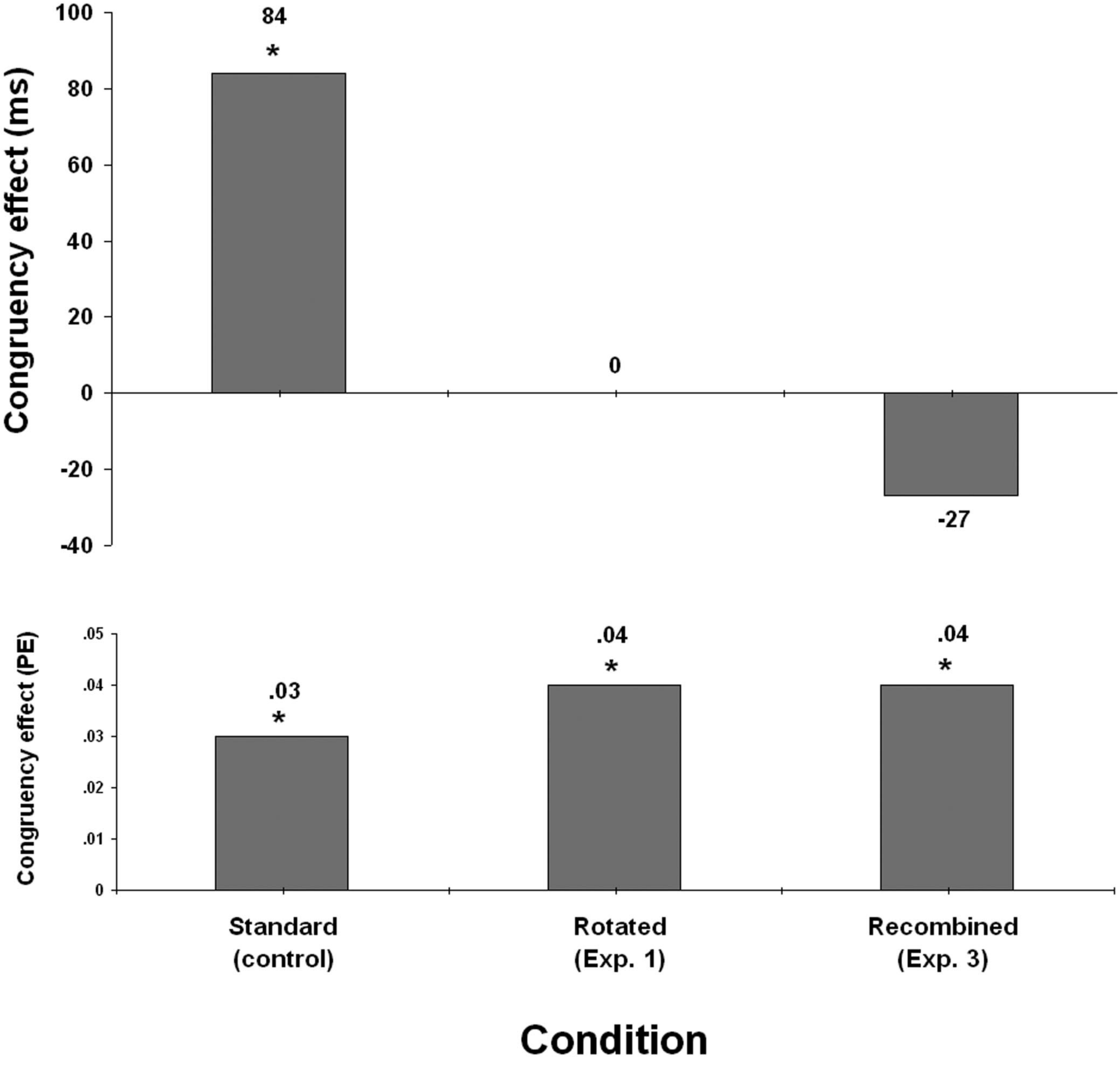

Figure 4. Congruency effect in reaction time and proportion of errors (PE) as a function of condition: Experiments (Exp.) 1 and 3.

group and these variables. On average, switching cost was reduced by increasing cue–target interval and was 116, 126, 94, and 62 ms in the four cue–target intervals, respectively.

PE

Switch, congruency, and cue–target interval were involved in a significant triple interaction as well as in significant (or marginal) main effects in all the two-way interactions. None of the effects involving group approached significance. The triple interaction indicates that the PE-TRCE declined with increasing cue–target interval among switch trials (.06, .06, .06, and .03 for the four intervals, respectively) but not among repeat trials (.02 in all the intervals).

Secondary RT Analyses

What codes support the TRCE? After a review of a large body of literature, Proctor and Cho (2006) recently concluded that categorical codes (such as up, down, right, and left in this case) are prevalent in speeded binary classification tasks, regardless of their spatial or nonspatial nature. Similar ideas are incorporated in several task-switching theories (e.g., Meiran, 2000a, 2000b; D. W. Schneider & Logan, 2005; Schuch & Koch, 2003), and other theorists have even suggested that the codes are verbal or semantic in nature (e.g., Goschke, 2000; Lien, Schweikert, & Proctor, 2003; Logan & Bundesen, 2004; Mayr & Kliegl, 2000; Miyake, Emerson, Padilla, & Ahn, 2004; D. W. Schneider & Logan, 2005; Schuch & Koch, 2003; Waszak, Hommel, & Allport, 2005).

An important index that allowed for a tentative characterization of the codes is based on Adam, Boon, Paas, and Umiltà's (1998) work. Specifically, these authors characterized effects as linguistically based by their relative late appearance. This late appearance was operationalized through an examination of the RT distributions and by showing that effects increased among the relatively slow responses. Accordingly, if the LTM codes that support the RT-TRCE are verbal or semantic in nature, the RT-TRCE should increase with response slowness in the control group. No such trend was predicted for the experimental group. This prediction was borne out. Specifically, in an analysis including the within-condition RT quartile (1st, 2nd, 3rd) as an independent variable obtained by Vincentizing (see Ratcliff, 1979), the triple interaction between quartile, group, and congruency was significant, $F(2, 44) = 6.50$, $MSE = 3{,}881.15$. In the control group, the RT-TRCE increased from 53 to 60 to 98 ms for the first, second, and third RT quartiles, respectively: $F(2, 22) = 3.43$, $MSE = 5{,}851.80$, $p = .05$, for the simple interaction between quartile and congruency within this group. In contrast, there was no such trend in the experimental group (0, 15, and −21 ms, respectively).[3] This interaction is also informative with respect to the lack of a group main effect, which seems surprising because one would expect a novel condition to produce slower RTs. Examining the significant triple interaction from the viewpoint of group differences shows that the control group was numerically faster in conditions in which their advantage could show up. These include the congruent condition (because according to our reasoning, incongruent trials are slowed when the task is familiar) and conditions in which the availability of verbal codes is mostly evident—that is, among the relatively slow trials. In detail, although the control group was slower in incongruent trials by 20, 7, and 24 ms in the three quintiles, respectively, they were faster in congruent trials by 22, 37, and 75 ms, respectively.

Did the groups differ from one another in the presence or absence of task switching? One could argue that by changing the setup, we created a situation in which the control group switched tasks while the experimental group did not. According to this argument, participants in the experimental group selected among eight stimuli, each made of a cue and target combination.[4] The absence of an RT-TRCE in the experimental group, according to this idea, could be entirely due to the absence of task switching. It is therefore important to show that task switching took place in the experimental group as much as it took place in the control group. We used two indices to verify this but acknowledge the fact that these indices are inconclusive. One index is switching cost. The status of this effect as an index of switching cost is still debated (see especially Logan & Bundesen, 2003; D. W. Schneider & Logan, 2005). Nonetheless, two recent studies by Dreisbach, Goschke, and Haider (2006, 2007) provided compelling evidence that switching cost at least indicates a subjective perception of the situation as one involving task switching. Specifically, when the paradigm in their experiments was described as involving S-R translations, there was no switch cost. When it was described as involving task switching, there was switching cost (mainly due to slowing in the switch condition). Moreover, participants who began performing after receiving the S-R instructions started showing switching cost only when the instructions were changed to task-switching instructions.

The other signature we used was the well-established interaction between task switching and response repetition. According to this interaction, response repetition is facilitatory in the context of task repetition but results in slowing in the case of a task switch. The reason why we focused on this interaction is that all the existing accounts of this interaction are based on the assumption that task switching took place (e.g., Hübner & Druey, 2006; Kleinsorge & Heuer, 1999; Mayr & Bryck, 2005; Meiran, 2000a; Rogers & Monsell, 1995; Schuch & Koch, 2004). Moreover, D. W. Schneider and Logan (2005), who recently extended Logan and Bundesen's (2003) theory that assumes no task switching, explicitly mentioned this interaction as something that their model, as currently developed, does not account for. Finally, in this literature, researchers make a distinction between "true" task-switch effect and a cue-switch effect. To separate these two components, they use two different cues for each task (e.g., high–low and vertical), thus creating conditions involving task repetition plus cue repetition, task repetition plus cue switch, and a task-switch condition. The "true switch cost," according to this framework, is the difference between the switch condition and the cue-switch task-repeat condition. Using this approach, Mayr and Kliegl (2003) showed that response repetition interacted with the "true" switch cost but did not interact with the cue-repetition effect. According to this line of reasoning, the presence of an interaction between task switching and response repetition can be taken as evidence for the presence of a "true switch effect."

Note that the argument we wish to support here is relatively weak. According to this argument, the two groups in our experiment did not differ from one another in the degree to which they switched tasks. We do not make the more general argument that switching cost and the Switch × Response Repetition interaction constitute ultimate proofs that switching took place in the control group.

With respect to switching cost, it was statistically the same in both groups, as reported already. This was also true for the interaction between switching and response repetition, $F(1, 22) = 52.65$, $MSE = 1{,}708.31$, which was statistically the same for the two groups, as indicated by a clearly nonsignificant interaction involving group, switch, and response repetition, $F(1, 22) = 0.04$, $MSE = 1{,}708.31$ (see Figure 5). Thus, as far as we can tell, task switching took place to the same degree in both groups.

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[3] The quartiles were computed within each of the cells of the design described in Table 1. Thus, the variations due to condition did not affect the results of the present analysis.

[4] A related idea is suggested by Logan, Bundesen, and Schneider (e.g., Logan & Bundesen, 2003; D. W. Schneider & Logan, 2005). Note, however, that these authors argued that there is no task switching even in the standard setup that was used in the control group but assumed that abstract response categories are nonetheless used (D. W. Schneider & Logan, 2005). The question posed here is somewhat different and refers to the possibility that there was task switching only in the control group.

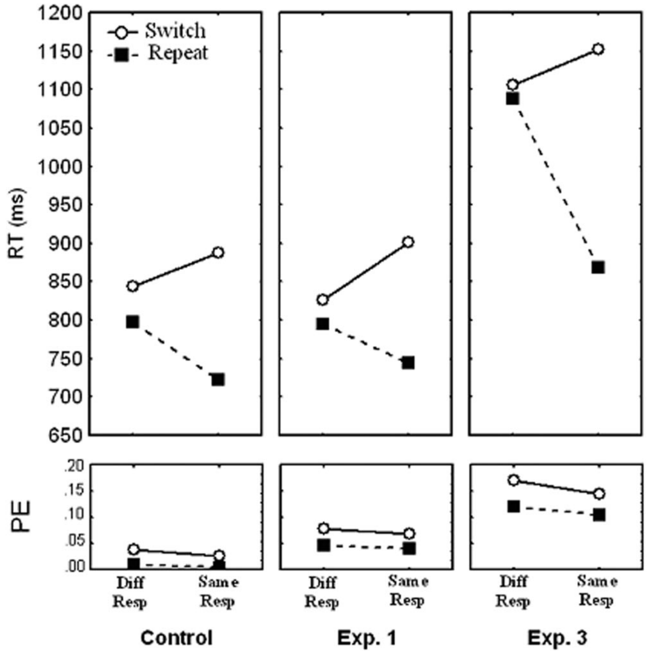

Figure 5. Mean reaction time (RT) as a function of switch and response repetition: Experiments (Exp.) 1 and 3. PE = proportion of errors; Diff = different; Resp = response.

Within-session practice effects. An interesting question is whether the novel task rules or task-related codes were sufficiently well learned in the course of the single session and gave rise to an RT-TRCE. We addressed this question by including block (1–4) as an additional variable in the ANOVA, which, this time, we performed only on the experimental group. One participant was not included in this analysis because of the relatively high number of errors made, resulting in zero trials in one of the 64 design cells. Block did not enter any significant interaction; most important, it did not interact significantly with congruency, $F(3, 30) = 1.34$, $MSE = 16{,}307$, $p = .28$. The RT-TRCE was numerically negative in Blocks 2 and 4 (−28 and −5 ms, respectively) and numerically positive in Blocks 1 and 3 (19 and 18 ms, respectively), none of which reached significance.

Summary

The results of this experiment were as predicted by our hypothesis. The RT-TRCE was present in the control condition but not in the rotated condition. Moreover, in the control condition, the RT-TRCE increased with response slowness and was present in the entire RT distribution.

Experiment 2

Experiment 2 involved a six-session practice with exactly the same procedure used in Experiment 1. We predicted that such extensive practice would result in the automatization of the novel response category codes that were used in the experimental group and in the consequent emergence of an RT-TRCE.

Method

Participants

Twelve undergraduates from Ben-Gurion University of the Negev and from the affiliated Sapir College participated in the experiment. All of them reported normal or corrected-to-normal vision. The participants were paid 25 NIS (about $5.50 in U.S. currency) per hour or else received course credit in return for their participation. Two participants were excluded from the analysis due to an exceptionally high error rate of 13% and 34% as compared with 0.5%–2% among the remaining participants. Accordingly, the final analysis was conducted on the results of 10 participants. Analyses without excluding participants yielded similar results.

Procedure

The experiment included six identical sessions, all conducted within 9 days. The procedure in each session was identical to that used in the experimental group in Experiment 1.

Results

We used the same trial exclusion criteria as before, which resulted in the exclusion of 1% of the RTs, or those that fell outside of the 100- to 3,000-ms range. Because the initial stages of learning produce the largest impact on performance, we broke down the first session data into four blocks. Thus, our primary independent variable, practice, had nine values: the four blocks of Session 1 and Sessions 2–6. The main ANOVAs were conducted with practice, cue–target interval, task switch, and congruency as within-participant independent variables (see Table 2).

RT

The most relevant interaction involves practice and congruency (see Figure 6). This interaction was significant. There was a slight nonsignificant reversed congruency effect in Block 1. In Blocks 2 and 3, the congruency effect was significant ($p < .05$ in both cases), and in Block 4 it was positive but far from significant ($F < 1.0$). When the four blocks of Session 1 were pooled, the TRCE was nonsignificant, $F(1, 9) = 1.05$, $MSE = 35{,}175.34$.

Although the trends for the first session are more jumpy than in Experiment 1, the replicable pattern across the two experiments concerns the lack of a stable RT-TRCE in this session. In contrast, the RT-TRCE was significant in Sessions 2–6 ($p < .05$ in all five comparisons) and ranged between 25 and 34 ms. The aforementioned interaction was qualified by the significant four-way interaction. Nonetheless, the trend of the Practice × Congruency interaction remained qualitatively the same. In Session 1, the RT-TRCE was unstable. Ten of the 32 RT-TRCE comparisons in Session 1 indicated a reversed effect (31.3%, each comparison conducted within a condition defined by cue–target interval [4], block [4], and switch [2]). Across these 32 comparisons, the RT-TRCE ranged between −89 and 99 ms. In Sessions 2–6, the trend of a positive RT-TRCE was stable. Only 1 of the 40 (2.5%) comparisons was negative (−3 ms) with the remaining 39 comparisons ranging between 5 and 63 ms. (The conditions

Table 2
Analysis of Variance Tables—Experiment 2

Effect	*df*	*RT* *F*	*RT* *MSE*	*RT* *p*	PE *F*	PE *MSE*	PE *p*
Practice	8, 72	20.61	112,895.10	<.05	2.52	.0127	<.05
Cue–target interval (CTI)	3, 27	23.62	30,502.86	<.05	3.15	.0007	<.05
Switch	1, 9	32.91	44,399.76	<.05	14.42	.0026	<.05
Congruency	1, 9	5.56	35,918.40	<.05	8.14	.0103	<.05
Practice × CTI	24, 216	2.56	4,761.20	<.05	0.70	.0007	.85
Practice × Switch	8, 72	9.77	6,807.16	<.05	1.76	.0014	.10
CTI × Switch	3, 27	14.09	7,642.19	<.05	4.75	.0010	<.05
Practice × Congruency	8, 72	2.39	6,971.55	<.05	2.26	.0055	<.05
CTI × Congruency	3, 27	0.13	2,905.73	.94	0.41	.0009	.75
Switch × Congruency	1, 9	5.42	4,931.76	<.05	12.78	.0013	<.05
Practice × CTI × Switch	24, 216	2.60	4,674.63	<.05	0.95	.0007	.53
Practice × CTI × Congruency	24, 216	1.29	3,995.94	.17	1.34	.0009	.14
Practice × Switch × Congruency	8, 72	0.79	3,700.71	.61	0.25	.0006	.98
CTI × Switch × Congruency	3, 27	0.24	4,273.36	.87	1.83	.0008	.16
4-way interaction	24, 216	1.78	4,254.91	<.05	1.22	.0007	.23

Note. PE = proportion of errors.

for the 40 comparisons were defined by the same variables except that the practice condition was defined by session [5] and not by block.)

The significant triple interaction involving practice, switch, and cue–target interval is noteworthy (see Figure 7). Of interest is the question of whether switch effects are eliminated by such an extensive practice. The results show that even in Session 6, there was a relatively substantial switch effect in the short cue–target intervals (48 and 49 ms for cue–target interval = 0 and 300 ms, respectively) that diminished to 19 and 16 ms in the two long intervals, respectively. This switch cost was significant for the first three intervals, $F(1, 9) = 47.64$, 18.01, and 31.21, $MSE =$ 17,659.88, 33,533.32, and 9,866.38, respectively; and approached significance for the fourth interval, $F(1, 9) = 4.42$, $p = .06$, $MSE = 6{,}246.74$. In summary, there were substantial switch costs even in Session 6. Their absence in the long cue–target interval in Session 6 could be explained as a result of advance preparation. Meiran, Chorev, and Sapir (2000) also observed the elimination of switch costs by preparation after extensive practice.

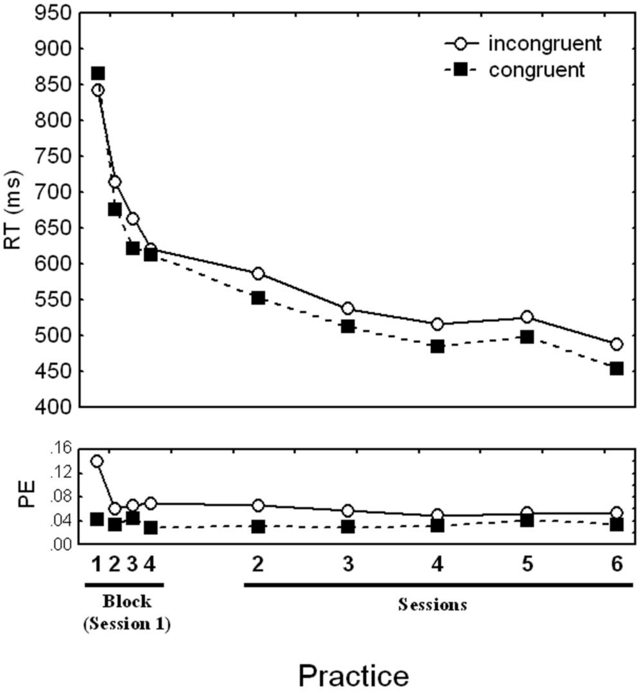

Figure 6. Mean reaction time (RT) and proportion of errors (PE) as a function of congruency and practice: Experiment 2.

PE

Practice had a significant main effect as well as a significant interaction with congruency. These practice effects reflect a reduction from a PE of .07 and .02 (incongruent and congruent, respectively) in the first block of Session 1 as compared with a PE of .01 to .02 and .00 to .01 (incongruent and congruent, respectively) in the remaining blocks and sessions. PE was also slightly but significantly affected by cue–target interval, but this trend interacted with switch. In switch trials, the PE was .03, .02, .01, and .01 in the four intervals, respectively, whereas in repeat trials, it was .00 in the first three intervals and .01 in the last interval. Switching affected incongruent trials (.03 and .01 in switch and repeat trials, respectively) but not congruent trials (close to .00 in both switch and repeat trials).

In order to characterize the codes contributing to the reestablished RT-TRCE, we examined the interaction between quartile (1st, 2nd, and 3rd) and congruency in Sessions 2–6, where the effect was consistently found. This interaction did not reach significance, although the numerical trend indicated an increase in the RT-TRCE with a response slowness of 23, 28, and 34 ms in the three quartiles, respectively, $F(2, 18) = 2.07$, $p = .15$. We also examined the linear component of this interaction in an effort to increase the statistical power of the comparison, and it, too, did not reach significance, $F(1, 9) = 2.24$, $p = .16$.

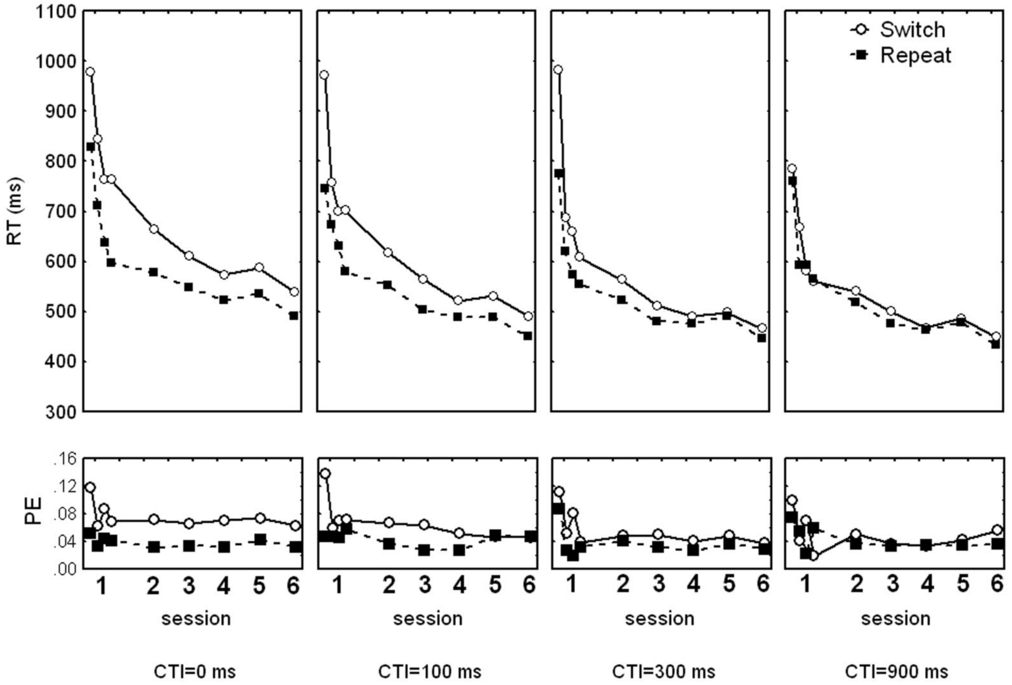

Figure 7. Mean reaction time (RT) as a function of cue–target interval (CTI), switch, and practice: Experiment 2. PE = proportion of errors.

Summary

The results of this experiment show that although the RT-TRCE was not consistently found in Session 1, largely replicating Experiment 1, it was significant in Sessions 2–6. Of interest is why the RT-TRCE appeared starting with Session 2 rather than growing gradually with practice. An intriguing possibility is that a night's sleep was required to consolidate the LTM trace, as has been found for a variety of LTM codes (Karni, Tanne, Rubenstein, Askenasy, & Sagi, 1994; Stickgold, 1998). We note the fact that the RT-TRCE that we found in Sessions 2–6 was numerically much smaller than in the control group of Experiment 1 (~30 ms as compared with ~85 ms). Moreover, unlike in the control condition, the RT-TRCE we observed did not increase (as much) with response slowness. We will return to this issue in the General Discussion.

Experiment 3

Experiments 1 and 2 supported the hypothesis that LTM codes subserve the RT-TRCE. An interesting question is whether these LTM codes involve direct S-R translation rules (the nonmediated route in Figure 1) or whether they involve mediation through abstract response category codes (the main route in Figure 1). By direct S-R translation, we mean rules of the sort "IF task is up–down and target is up–left, THEN press the *7* key on the number pad."

Note that this rule links the stimuli directly to the keypress. By mediated rules, we mean rules such as "The positions above the midline indicate *up,* and the positions below the midline indicate *down*. *Up* is indexed by pressing the *7* key on the number pad, and *down* is indexed by pressing the *3* key on the number pad." Note that first the stimulus is mapped to an abstract response category (such as *up* or a certain part of the display) and, second, the abstract representation is mapped to an overt response—a keypress. Also note that mediated rules often involve semantically related representations. For example, the mediators *up* and *down* are both semantically related to the concept of verticality. As such, the mediators could be described as (a part of) a task set, being activated and suppressed as a group.

There are a number of findings suggesting that the rules are grouped into tasks. These findings are therefore consistent with the mediation hypothesis. First, Arbuthnott (2005) examined backward inhibition effects. These effects reflect slowing in task-switch trials in conditions involving a repetition of the *n*-2nd task. For example, the last trial in the A-B-A sequence of tasks is usually slower than the comparable trial in a C-B-A sequence (where A, B, and C represent different tasks). These inhibition effects are commonly taken as evidence for the suppression of the abandoned task rule (rather than a specific S-R rule; e.g., see Arbuthnott & Frank, 2000; Mayr & Keele, 2000; Schuch & Koch, 2003). It is important to note that Arbuthnott (2005) showed that conditions in which backward inhibition was small were associated with larger RT-TRCEs, suggesting that the RT-TRCE represents incomplete suppression of a competing task set. The second piece of evidence is that the PE-TRCE (Meiran & Daichman, 2005) as well as the RT-TRCE (e.g., Cepeda et al., 2001; Koch & Allport, 2006; Meiran, 2005) increase following a task switch. These results may be interpreted as evidence that the execution of the alternative task set in the previous trial primed its response codes, which resulted in an elevated TRCE. Again, the point here is that what had been primed is the task as a whole rather than individual S-R translation rules.

The evidence in favor of the S-R rule hypothesis appears less clear-cut. On the one hand, Kiesel et al. (2007) showed that the RT-TRCE was elevated in conditions involving stimulus repetition. On the other hand, Koch and Allport (2006) associated each task with a different stimulus set and found that reversing this stimulus-to-task assignment incurred a performance cost. Of importance, the cost due to stimulus–task rearrangement was statistically additive with the RT- TRCE. If the TRCE results from a link between specific stimuli and responses, changing the entire stimulus set is expected to reduce the effect, something that did not happen in Koch and Allport's experiments.

We addressed the question concerning rule type by recombining the visual elements of the standard display in a manner that made it extremely difficult (perhaps even impossible) to form a strategy based on abstract response categories. Yet, using an S-R rule strategy (as we define it) was at least as easy as it was in Experiments 1 and 2 and in the control group against which the recombined condition was compared. Specifically, the S-R-based strategy as we define it was one relying on a verbal description of the cue and the target displays. Verbalizing each of these elements was at least as easy in Experiment 3 as it was in Experiments 1 and 2 and the control group. In detail, the target display was the same as that used in the control condition. The "cue" is therefore the only element of the stimulus that could create a difference. This cue appears to be no more difficult to describe in words in comparison with the cues used in the rotated condition of Experiments 1 and 2. For example, the cue presented in Figure 2 (Experiment 3) could be described as an "upper-left corner," whereas the cue used in Experiment 1 could be described as "an upper-left arrow." Accordingly, an S-R translation rule in the present experimental group could be phrased as follows: "IF task is upper-left corner and target is *up–left,* THEN press the *7* key on the number pad."

Congruency was defined in the present experiment in the same way it was defined in the previous ones. Namely, congruent trials were defined as those in which the same target stimulus, when paired with the two different "task cues," indicated the same response key. Incongruent trials were defined as those in which the keypress response to a given target stimulus depended on the "task cue" (see Figure 8).

Method

Participants

Thirteen undergraduate students were assigned to the experimental group. The control group was the same as in Experiment 1. (The reader is reminded that Experiments 1 and 3 were run as a single experiment.) One participant from the experimental group committed an error rate of 81%, as compared with the mean of 18% in that group, and was therefore excluded from the analyses. Half of the 12 participants whose results were analyzed used the keys *1* and *9* on the keypad. The other half of the participants used the keys *3* and *7.*

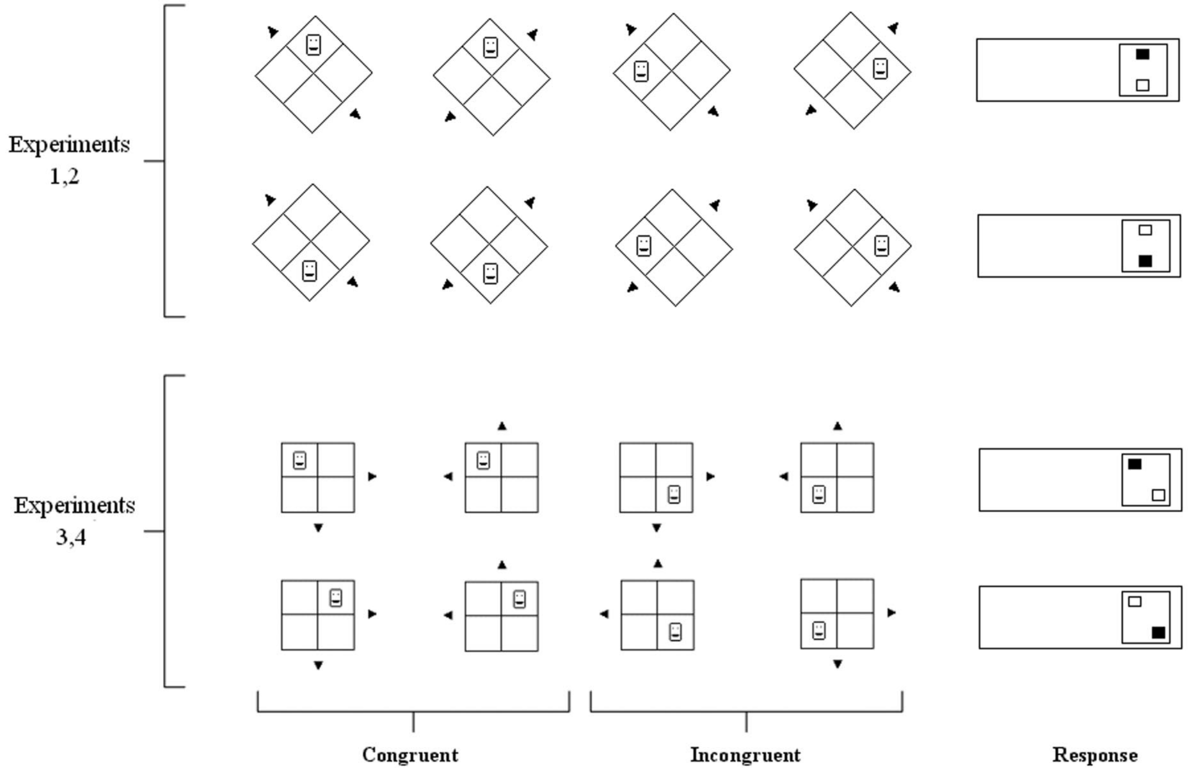

Figure 8. Cue–target compounds and their mapping to response keys in the experimental conditions (one example of the eight mappings used in Experiments 3 and 4 is presented).

Stimuli and Procedure

For the experimental group, the task cues were composed of two arrow heads, either pointing up and left or pointing down and right. Four arbitrary S-R mappings were used and were counterbalanced between participants (see Figure 8 for an example of one mapping). Each mapping included eight compounds of task cue and target. Four compounds were allocated to each response key. In addition, four compounds were congruent—that is, the target could lead to the same response under either task—and four compounds were incongruent. Before the practice phase of the experiments, the participants were given a few minutes to rehearse the S-R mapping. The procedure (namely, block and trial structure) was otherwise identical to that in Experiment 1.

Results

We analyzed the results of the present experimental group together with those of the control group, which also served in Experiment 1. Of the RTs, 2% fell outside the 100- to 3,000-ms range and were not analyzed. Table 3 presents the RT ANOVA results.

RT

Unlike in Experiment 1, there was a significant main effect for group, where the experimental group was slowed by 252 ms relative to the control group. The usual switch, cue–target interval, and Switch × Cue–Target Interval effects were observed and were statistically the same for both groups, although only the last interaction approached significance. It indicated the usual (albeit a bit jumpy) trend. Switch costs were 126, 161, 122, and 95 ms in the four cue–target intervals, respectively.

The most important findings concern congruency, which interacted significantly with group (see Figure 4). Whereas a positive and significant congruency effect was observed in the control condition (already reported in Experiment 1), the numerical trend indicated a reversed congruency effect in the experimental condition, although it did not reach significance, $F(1, 22) = 1.06$, $p = .36$. In the experimental group, only three out of the eight conditions (38%) produced a numerically positive RT-TRCE. These eight conditions were defined according to cue–target interval and switch. The positive but nonsignificant RT-TRCE (Fs $< .5$) was 7, 7, and 23 ms for cue–target intervals of 0, 100, and 300 ms, respectively, all involving a task switch. It is important to note that the present results also rule out general slowing as an account of the RT-TRCE because the slow condition produced a smaller RT-TRCE.

A somewhat unusual significant interaction was found between cue–target interval and congruency. This interaction indicated an increased RT-TRCE for cue–target interval of 600 ms (70 ms) as compared with 9, 28, and 10 ms for cue–target intervals of 0, 300, and 900 ms, respectively. This was entirely due to the fact that the RT-TRCE was reversed numerically in the experimental group in all the cue–target intervals except for the 600-ms interval, in which the effect was numerically positive.

PE

There was a significant main effect for group, reflecting the higher PE in the experimental group (.13) than in the control group (.02). In addition, there were significant main effects of congruency, switch, two-way interactions between congruency and switch and between congruency and cue–target interval, and a significant triple interaction between cue–target interval, congruency, and switch. All these were qualified by a significant quadruple interaction. In switch trials, the control group showed a PE-TRCE that was .06 when the cue–target interval was up to 600 ms and .02 when it was 900 ms. No such trend was seen in the experimental group (PE-TRCE = .04, .09, .07, and .05 in the four cue-target intervals, respectively). In repeat trials, the control group showed a negligible PE-TRCE of .00 in the shortest cue–target interval and .01 in the remaining intervals. The experimental group showed a jumpy trend in PE-TRCE of .02, −.01, .07, and .03 in the four cue–target intervals, respectively.

Table 3
Analysis of Variance Tables—Experiment 3

		RT			PE		
Effect	*df*	*F*	*MSE*	*p*	*F*	*MSE*	*p*
Group	1, 22	13.72	443,813.64	<.05	12.50	.1003	<.05
Cue–target interval (CTI)	3, 66	27.33	14,045.68	<.05	0.67	.0016	.57
Switch	1, 22	65.13	23,488.54	<.05	40.24	.0022	<.05
Congruency	1, 22	2.78	29,844.17	.11	17.91	.0074	<.05
CTI × Group	3, 66	1.59	14,045.68	.20	1.60	.0016	.20
Switch × Group	1, 22	2.05	23,488.54	.17	3.76	.0022	.07
Congruency × Group	1, 22	9.75	29,844.17	<.05	1.53	.0074	.23
CTI × Switch	3, 66	2.42	7,121.22	.07	0.58	.0021	.63
CTI × Congruency	3, 66	2.94	6,526.52	<.05	4.12	.0009	<.05
Switch × Congruency	1, 22	4.50	8,519.13	<.05	12.94	.0030	<.05
CTI × Switch × Group	3, 66	0.26	7,121.22	.85	0.71	.0021	.55
CTI × Congruency × Group	3, 66	0.14	6,526.52	.94	1.88	.0009	.14
Switch × Congruency × Group	1, 22	1.12	8,519.13	.30	0.00	.0030	1.0
CTI × Switch × Congruency	3, 66	0.01	8,869.10	.997	4.54	.0012	<.05
4-way interaction	3, 66	0.43	8,869.10	.73	3.35	.0012	<.05

Note. PE = proportion of errors.

Secondary RT Analyses: Did the Groups Differ From One Another in the Presence or Absence of Task Switching?

To answer this question, we used the same criteria as before. First, the switch effects were statistically the same for both groups, as reported already. Second, a significant interaction between switch and response repetition was found in both groups, *F*(1, 22) = 52.36 and 10.56, *MSE* = 4,036.70, for the simple interaction between group and response repetition within the experimental and control groups, respectively. In fact, it was exaggerated in the experimental group, as seen in a significant interaction involving group, switch, and response repetition, *F*(1, 22) = 7.94, *MSE* = 4,036.70. Thus, as far as we can tell, the groups did not differ (much) in this respect.

Summary

The results of the present experiment show that the RT-TRCE was eliminated in a condition in which it was difficult, if not impossible, to come up with abstract response categories linking stimuli to responses, so that performance was probably based on an S-R translation strategy. It is interesting to note that in the post-experimental debriefing the participants reported that they attempted to construct task-related rules. However, these rules turned out to be very complex and did not involve response categories. Also interesting is the fact that disabling the use of abstract task-related mediators resulted in a substantial performance decrement seen in both RT and PE. We would argue that the absence of RT-TRCE resulted from the fact that the tasks were novel. The fact that performance was impaired in general was due to the inability to use abstract mediators.

Experiment 4

Experiment 4 was a practice experiment in which the participants executed the same procedure as used in Experiment 3 in six separate sessions. Although practice effects were obviously predicted, we predicted that, unlike in Experiment 2, in which practice led to the reinstatement of the RT-TRCE, no such reinstatement of the effect would be found here. These predictions were based on the assumption that the critical codes involve response categories rather than individual S-R translation rules.

Method

Participants

Twelve undergraduates from Ben-Gurion University of the Negev participated in the experiment. All of them reported normal or corrected-to-normal vision. The participants were paid 25 NIS (about $5.50 in U.S. currency) per 1-hr session in return for their participation. Two participants were excluded from the analysis because, as a result of having committed too many errors, they had conditions with no valid trials to analyze.

Procedure

The experiment included 6 sessions, all conducted within 10 days. The procedure and stimuli in each session were identical to those in the experimental group of Experiment 3.

Results

On the basis of the same trial exclusion criteria as before, 1% of the RTs fell outside the 100- to 3,000-ms range and were not analyzed. Table 4 presents the RT ANOVA results.

RT

There were main effects and two-way interactions involving switch, cue–target interval, and practice, but all of them are qualified by the significant triple interaction of these three variables. As seen in Figure 9, the switch effect was positive in all but two cases. These cases involve the last two sessions, and the cue–target interval was 900 ms. Of importance, the switch effect in Session 6, for the three shortest cue–target intervals, remained positive (69,

Table 4
Analysis of Variance Tables—Experiment 4

		RT			PE		
Effect	*df*	*F*	*MSE*	*p*	*F*	*MSE*	*p*
Practice	8, 72	33.49	121,535.46	<.05	5.98	.0314	<.05
Cue-target interval (CTI)	3, 27	17.90	40,919.04	<.05	5.54	.0029	<.05
Switch	1, 9	58.37	48,050.37	<.05	27.61	.0081	<.05
Congruency	1, 9	0.06	205,525.76	.81	3.86	.0668	.08
Practice × CTI	24, 216	1.80	15,188.72	<.05	2.18	.0020	<.05
Practice × Switch	8, 72	8.19	17,124.66	<.05	1.52	.0050	.17
CTI × Switch	3, 27	7.12	15,830.59	<.05	1.85	.0047	.16
Practice × Congruency	8, 72	1.08	27,880.26	.38	0.96	.0159	.47
CTI × Congruency	3, 27	0.63	12,031.83	.60	0.86	.0042	.47
Switch × Congruency	1, 9	6.93	27,633.86	<.05	10.63	.0040	<.05
Practice × CTI × Switch	24, 216	1.68	13,643.53	<.05	1.45	.0035	.09
Practice × CTI × Congruency	24, 216	0.64	12,242.92	.90	0.96	.0025	.51
Practice × Switch × Congruency	8, 72	1.06	15,661.44	.40	0.27	.0050	.97
CTI × Switch × Congruency	3, 27	0.13	13,664.60	.94	0.77	.0042	.52
4-way interaction	24, 216	0.72	12,774.69	.83	0.65	.0036	.89

Note. PE = proportion of errors.

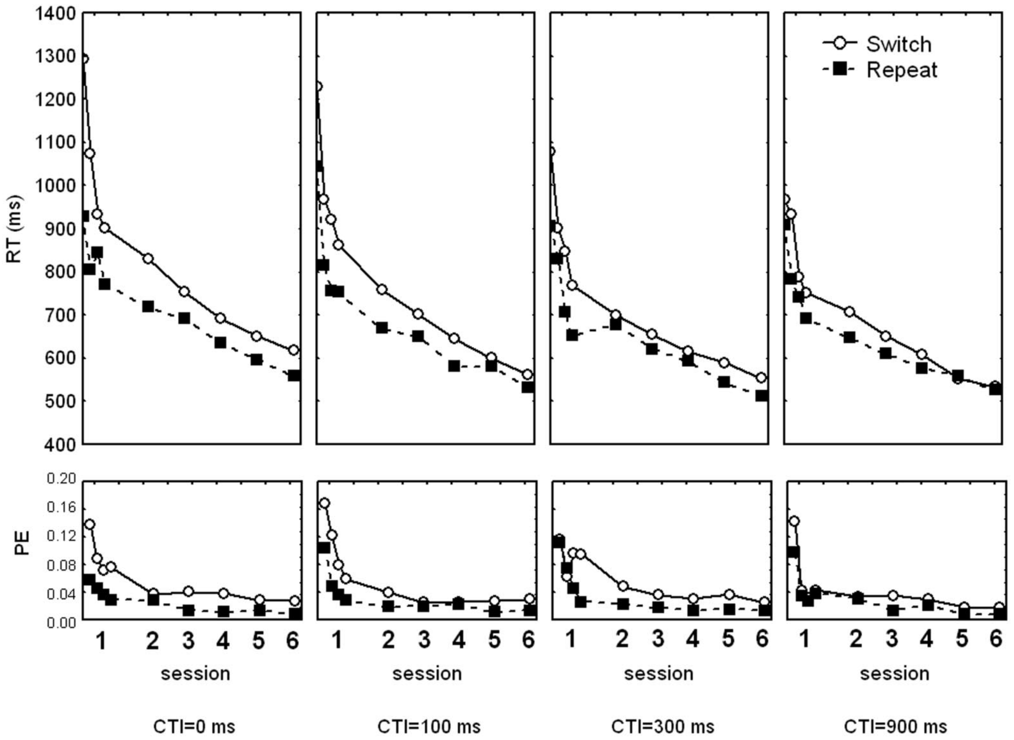

Figure 9. Mean reaction time (RT) as a function of practice, cue–target interval (CTI), and switch: Experiment 4. PE = proportion of errors.

31, and 41 ms for cue–target intervals of 0, 300, and 600, respectively) and was significant in the first two intervals, $F(1, 9) = 34.16$ and 7.49, $MSE = 1{,}022.43$ and 1,241.43, respectively, and approached significance in the third interval, $F(1, 9) = 4.64$, $p = .06$, $MSE = 3{,}633.40$.

The only significant effect involving congruency was its interaction with switch. The congruency effect was positive in the switch condition (29 ms) and reversed in the repeat condition (17 ms), although neither was significant ($p = .33$ and .46, respectively).

Figure 10 reveals a reversed effect in the beginning stage of practice, as also found in Experiment 3. The trend became positive in Sessions 3–6 (9, 16, 14, and 8 ms, respectively) but was far from significant ($p > .20$).

PE

Significant main effects were found for practice, switch, and cue–target interval. In addition, there were significant interactions between practice and cue–target interval and between switch and congruency. The first interaction reflects the fact that practice effects produced a gradual and steady reduction in PE rates so that by Session 2, PE rate was .02 in all the cue–target intervals and remained at that level until Session 6. In contrast, in Block 1–Session 1, this rate was largest for the cue–target interval of 300 ms (.14), intermediate for cue–target intervals of 600 and 900 ms (.12), and smallest for the cue–target intervals of 0 ms (.11). As found before, the PE-TRCE was larger in switch trials (.04) than in repeat trials (.02).

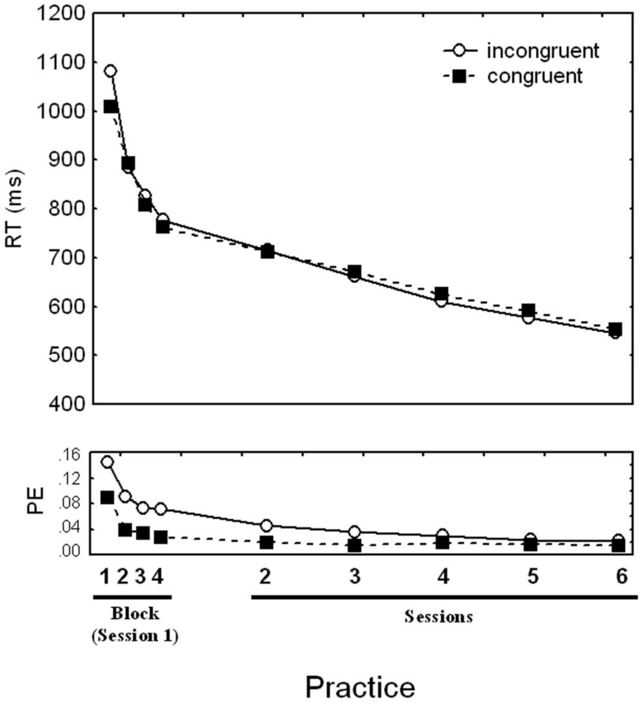

Figure 10. Mean reaction time (RT) and proportion of errors (PE) as a function of congruency and practice: Experiment 4.

Summary

The results of the present experiment show that there was no reliable RT-TRCE in this paradigm even after extensive practice. Nonetheless, there was a substantial practice effect, indicating (by definition) the formation of some form of LTM. These results suggest that whatever LTM traces were formed during practice did not produce an RT-TRCE.

Discussion of Experiments 3 and 4

The results show that when it is extremely difficult (or even impossible) to generate abstract task-related response category codes, the RT-TRCE is absent and remains absent even after extensive practice. Still, as much as we could tell, the experimental and the control groups did not differ from one another in the presence of task switching. The question, then, is how this could be. A possible answer is that although the rules involved individual S-R translations, these groups were chunked. Such chunking is to be expected given the fact that the cue was presented in advance, making it possible to retrieve the subset of S-R rules related to that cue in advance.

Of interest, our results also show that an S-R translation strategy made performance more difficult and point to the relevant processing stage. Specifically, the results implicate response selection rather than task switching as the locus. The fact that S-R rules did not complicate task switching is made evident by two facts. First, switching effects were comparable in size to those seen in the control group. Second, the PE-TRCE was also comparable in size in the two groups. It is important to note that the PE-TRCE consists of evidence for the execution of the wrong task rule (Meiran & Daichman, 2005).

If we accept this logic, the next conclusion is that the increased error rate and the slower performance seen in the experimental group should be interpreted as resulting from the complication of response choices within a given task. To appreciate the rationale, consider the control condition and the up–down task as an example. Using abstract rules made response choices easier because it broke down an otherwise complex decision into a series of simple computational steps. (Here we mean that the series-of-processing stage may even be arranged in a cascade in the sense described by McClelland, 1979.) In this example, the first computational step involved translating the cue into the exact rule to be used (which could be selecting the subset of abstract mediators), the next step involved translating the target position into *up* and *down* codes, and the last step involves translating the *up* and *down* codes into their respective keypresses. Now consider the S-R rules presented in Figure 8 and assume that the “cue” serves to retrieve the two related S-R rules. This scenario involved only two computational steps: Retrieve the chunk and apply the chunk. The preference given to abstract rules therefore obeys the conventional wisdom regarding using serial processing and doing only one thing at a time when tasks become complex. Although the conventional wisdom clearly applies to tasks performed over a long time, there is evidence that it also holds for tasks performed within hundreds of milliseconds. Logan and Gordon (2001) provided computational evidence that parallel performance in a complex situation is error prone, which is why serial processing is preferable. Luria and Meiran (2005) provided similar experimental evidence.

General Discussion

The present study provides evidence that the RT-TRCE reflects activated LTM in the sense described by Cowan (1988), Oberauer (2001), and Woltz and Was (2007), among others. In that respect, it provides an additional link between two core executive functions: WM and task switching.

Although our hypothesis concerning the origins of the RT-TRCE accords with already published results, the crucial aspect regarding the nature of the codes as LTM-based has not yet been established. To establish this assumption, we compared a task-switching paradigm based on familiar tasks with two closely matched paradigms in which the tasks were novel in the sense of not being linked to abstract response categories that were stored in LTM prior to testing. In addition, we also examined how practice (which supposedly forms LTM traces) affected performance. In an attempt to further characterize the codes, we also examined the influence of response slowness on the RT-TRCE.

Our results show that when the tasks were associated with familiar (LTM-based) response categories, the RT-TRCE was relatively large (~85 ms) and its size increased with response slowness. When the tasks were novel and unpracticed, so that no response categories were in LTM prior to the experiment, the RT-TRCE was eliminated. When the tasks were novel, permitting the formation of response categories, and were practiced (even for one session), the RT-TRCE was reliable, but its size was relatively modest (around 30 ms), and it did not increase with response slowness. Finally, when the tasks were novel but were designed in a way that made the generation of abstract response category codes extremely difficult, the RT-TRCE was absent and remained absent even after six sessions of practice.

The present results are consistent with the hypothesis that the RT-TRCE reflects activated LTM and not to the newly instructed task rules proper. If the newly instructed rules were responsible for the effect, then an RT-TRCE should have been found for the novel tasks that we used. The activated LTM could involve representations such as *up* or *left*, which serve as abstract response categories. This interpretation would support Cowan’s (1988) and Oberauer’s (2001) views. Alternatively, the activated LTM could involve a procedure such as relating a given stimulus to a given category, which accords with Woltz and Was’s (2007) view. The present results cannot point to which of these two alternatives is the correct view. Either way, the absence of the RT-TRCE in novel tasks suggests that the abstract response categories were either absent from LTM or have not yet been established or automatized. The emergence of the RT-TRCE in Experiment 2 suggests that novel response categories were used during performance and were placed within LTM as a result of practice. The lack of RT-TRCE after practice in Experiment 4 suggests that the strategy used by the participants did not involve mapping of stimuli to abstract response categories or that if such categories were used, they were very complex and could not be automatized even after six sessions of practice.

The results also enable a preliminary characterization of the LTM codes as linguistic or nonlinguistic in nature. Specifically, the increase of the effect with response slowness is taken as evidence for the involvement of linguistic codes (Adam et al., 1998). Such an increase was found where simple linguistic codes such as *up, down, right,* and *left* could be used and was not found in conditions (Experiment 2) in which the codes needed to be either linguistic but complex (e.g., up–left) or nonlinguistic. Furthermore, the increase was found where the RT-TRCE was relatively large.

There remains the question of why the RT-TRCE was considerably larger in the standard conditions than in the practiced rotated condition (Experiment 2). There are at least two possible reasons. One is that simple verbal codes, being so overly practiced, are more automatically accessed than newly practiced codes. Alternatively (or in addition), the standard condition is one enabling both simple linguistic codes and nonlinguistic codes. The present results cannot decide between these alternatives.

The results of Experiments 3 and 4 further show that the LTM codes that cause the RT-TRCE involve abstract mediation. Learning of stimulus codes (in the LTM portion in Figure 1) is insufficient to generate the RT-TRCE. The reason is that such learning was equally possible in Experiments 2 and 4, yet only in Experiment 2 did practice lead to the emergence of an RT-TRCE. What differentiates between the stimuli are the mediator codes. This conclusion is in agreement with some current theories of skill acquisition explaining single task performance. For example, Logan (1988) suggested that skillful automatic performance is based on the retrieval of instances from memory. Logan (1990) further concluded that these instances include an association between the stimulus and the abstract, task-dependent interpretation (e.g., "this is a word," "this is pronounceable") given to that stimulus, which is what we called the *abstract response category*. This conclusion accords with our suggestion regarding the effect of practice in generating abstract mediating codes that then give rise to the TRCE. Pashler and Baylis (1991), who suggested a drastically different theory than Logan's, also concluded that practice results in the strengthening of the link connecting the stimulus to the response via abstract response categories.

We note that a reliable PE-TRCE was found in most cases. On the basis of the results by Meiran and Daichman (2005), we argue that the PE effect, unlike the RT effect, could result from applying the currently irrelevant task rule, regardless of how this rule was implemented, and as such is not very informative. It could even result from the faulty coding of the task cue, for example.

In fact, we argue that the PE-TRCE and the RT-TRCE are separate phenomena and support this assertion by a double dissociation. One half of this double dissociation is provided in the current results, showing that some manipulations produced dramatic influences on the RT-TRCE while not affecting the PE-TRCE. The second half of the double dissociation is afforded by Yehene et al. (2005), who studied the neurological patient AF. When compared with controls, this patient exhibited drastically enlarged PE-TRCE. Yet, her RT-TRCE was normal (see also Meiran, Friedman, & Yehene, 2004).

How Are LTM Codes Activated?

An intriguing question is how the aforementioned LTM codes become activated (or highly accessible). One possibility is that they become activated as a result of task execution. However, we mentioned Yehene et al.'s (2005) study showing reliable RT-TRCE many trials after the competing task rule had last been applied. In that study, the authors further showed that the presence of RT-TRCE depended on whether a task switch was expected. For example, the RT-TRCE was eliminated in the last block of the experiment, in which a single task was instructed. These results seem to rule out an additional possibility that once the target stimulus has been linked to the competing task set, this set becomes activated unintentionally (Waszak, Hommel, & Allport, 2003). Had this been true, one would predict a TRCE even in single-task conditions that follow task switching, and this did not happen in Yehene et al.'s study (see also the single-task conditions in Rubin & Meiran, 2005). Accordingly, two recent works (Koch & Allport, 2006; Waszak & Hommel, 2007) have suggested that the unintentional retrieval of task sets operates at the abstract task level and not at the level of individual responses. Thus, it appears that the intention to be ready for a given task may be sufficient to activate its mediators in LTM. The advantage of this strategy is that the mediators either are already retrieved or are very easily retrievable. The only effortful or limited resource process remains the focusing of attention on the relevant subset of already activated codes (in agreement with Mayr & Kliegl, 2000). In that sense, task-switching situations do not involve complete reconfiguration of the system because most of the reconfiguration has been done before the switching block has begun. This last statement is in partial agreement with Logan and Bundesen's (2003) and D. W. Schneider and Logan's (2005) theories.

Abstract Task Rules Are Preferable

In the Discussion of Experiments 3 and 4, we listed one argument why abstract rules are preferable: because they break down a complex decision into a series of simple computations. Another reason concerns the ability to build on existing skills rather than building a new skill from scratch. Pashler and Baylis (1991) provided dramatic results that demonstrate this point. When the participants in their experiments were asked to associate categorizable stimuli (letters, digits, and symbols) to responses, there were large learning effects that were transferred to novel stimuli. When the choices were not categorizable (each response associated with particular digits and letters), learning did not transfer to novel stimuli, and more dramatically, performance on the familiar stimuli reverted to what it was in the beginning of the practice. These results indicate that participants need to build a skill from scratch in such cases.

Now consider the paradigm used in the control condition of Experiments 1 and 3. When asked to perform this paradigm, participants can rely on their overlearned skills of classifying locations as above, below, to the right, or to the left of a reference. When doing so, the only remaining novel aspect of the tasks is the mapping of the abstract codes (such as *up* and *left*) into the ad hoc selected responses (cf. Pashler & Baylis, 1991). The fact that the response keys also occupied relative positions that easily reminded participants of their association probably further encouraged the use of abstract rules.[5] Furthermore, typical task-switching experiments are introduced in ways that promote this attitude: The tasks

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[5] One condition in Meiran's (2005) study involved responding in an opposite manner (e.g., the lower key indicating *up* or the key on the left indicating *right*). This condition yielded the same pattern of results as in the standard condition, except for generally slowed responses. Thus, the use of response key positions that remind one of key meanings does not seem to be an essential aspect.

being chosen are usually familiar and are described as involving choices between abstract response categories.

Implications for Task-Switching Theories

We are aware of two formal theories of task switching that directly address the TRCE (Meiran, 2000a; D. W. Schneider & Logan, 2005).[6] In both of these theories, the effect arises because response selection involves two mappings or translations: One translation is between the stimulus and abstract response categories (such as *up* or *left*); the other is between the abstract category and the keypress. The TRCE results from the fact that the link between the abstract response category and its respective keypress remains strong for both tasks, including the irrelevant task. Thus, if the stimulus activates an abstract code that belongs to the wrong rule, this automatically translates into activation of the corresponding response. The fact that in both theories the stimulus first translates to an abstract response category is generally in agreement with the present findings because these categories are likely to reside in LTM.

Gilbert and Shallice's (2002) model is based on Cohen, Dunbar, and McClelland's (1990) connectionist model of the Stroop task. It describes switching between the two Stroop tasks, color naming and word reading. As argued above, the Stroop effect may not provide the proper analogy to the TRCE; the better analogy is the reverse Stroop effect. Gilbert and Shallice's model explains the reverse Stroop effect as follows: Word and color information both translate into discrete (abstract) interacting codes. Specifically, the code *red* used in the color pathway and the code *red* used in the word pathway facilitate one another. This gives rise to congruence effects (both Stroop and reverse Stroop effects). The reverse Stroop effect is usually not found because of the strong baseline activity of the word-processing pathway. However, when switching to the color task, the word-processing pathway is inhibited and the color-processing pathway is strengthened. Consequently, the color pathway becomes sufficiently potent and the word pathway becomes sufficiently weak to give rise to the reverse Stroop effect, which is found when switching from color naming to word reading. This model, too, is largely in agreement with our findings concerning the involvement of abstract codes as opposed to rules that link the stimulus directly to its response without the mediation of such rules. Note that what makes the codes abstract in this model is their links across processing pathways, which establish them as pathway independent at least to some degree.

Other Effects Involving Congruency

Several recent works have shown that incongruent trials result in increased control. This is seen in the current trials, in the form of the suppression of subliminal response priming effects (Kiesel et al., 2007). Increased control is also seen in sequential effects, where the effects of task switching (Goschke, 2000) as well as the effects of congruence (Brown et al., 2007; Kiesel et al., 2007) are modulated by the previous trial congruency status. Imaging work (Egner & Hirsch, 2005) and modeling work (Brown et al., 2007) suggest that these sequential effects, which reflect increased cognitive control, are mediated by increased task-related activation. This conclusion is generally in line with our idea that cognitive control over activated LTM is achieved by focusing on the relevant subset of representations.

Implications to Prefrontal Functions

In the introduction, we listed evidence that when the functioning of the prefrontal cortex is compromised, TRCE is elevated (Aron et al., 2004; Keele & Rafal, 2000). We also listed studies showing that oxygen consumption in the prefrontal cortex increases in incongruent trials relative to congruent trials (Konishi et al., 2003, 2005) and in the reverse Stroop effect, which we argue may be analogous to the TRCE (Woodward, Ruff, & Ngan, 2006). Our behavioral results indicate that the RT-TRCE results from activated abstract codes in LTM. Two competing hypotheses can be formed. According to the rule-representation hypothesis, the prefrontal cortex is where the abstract mediators are stored. This hypothesis is based on findings showing that this brain region is involved in the representation of abstract codes and rules (e.g., Sakai & Passingham, 2004; Wallis & Miller, 2003). According to the biasing hypothesis, the prefrontal cortex is the brain region that controls the activated LTM. Evidence for biasing comes from task-switching studies (Konishi et al., 2003, 2005; Mayr, Diedrichsen, Ivry, & Keele, 2005) as well as from tasks requiring controlled memory retrieval (Sakai & Passingham, 2004; for reviews, see Bunge, 2004; Miller & Cohen, 2001).

We tend to favor the biasing hypothesis because the evidence reviewed above shows that the TRCE is increased when prefrontal functioning is compromised. This finding suggests that compromising prefrontal functioning did not prevent the rules of the competing task from being represented. Moreover, Bunge (2004) provided evidence that the rules themselves are probably stored in posterior brain regions. In addition, Egner and Hirsch (2005) showed that the biasing affected posterior regions involved in task performance.

There are multiple mechanisms involving the prefrontal cortex that can create a bias in favor of the relevant task rule. Specifically, the left lateral prefrontal cortex has been implicated in the implementation of relevant rules in preparation for a task switch (for reviews, see Bunge, 2004; Derrfuss, Brass, Neumann, & von Cramon, 2005). In addition, the right prefrontal cortex has been associated with backward inhibition both in an imaging study (Dreher & Berman, 2002) and in a lesion study (Mayr et al., 2005). Accordingly, the right prefrontal cortex is expected to be related to an increased TRCE because lesser backward inhibition has been shown to increase the TRCE (Arbuthnott, 2005).

Conclusion

There are three main messages in the present article. The first message is that, being so prevalent, the RT-TRCE must be considered in theories explaining task switching. The second message concerns a specific hypothesis regarding the origins of the RT-TRCE, which was supported by the results of the present experi-

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[6] Brown, Reynolds, and Braver (2007) have recently proposed an elaborate model that explains sequential congruency effects in task switching. Because of this focus, the model does not address the exact type of cognitive representations involved in the TRCE, and we therefore decided not to discuss it in the present context.

ments. According to this hypothesis, abstract mediator codes are preferred and are used if just possible. If they are used repeatedly and consistently for a sufficiently long time, this results in the formation of highly accessible representations in LTM. When these codes are accessed, suppressing their activation becomes difficult, which results in the RT-TRCE. Our last message is that WM and task switching are closely related, as our hypothesis suggested.

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