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ORIGINAL ARTICLE

The reaction-time task-rule congruency effect is not affected by working memory load: further support for the activated long-term memory hypothesis

Yoav Kessler · Nachshon Meiran

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Abstract Previous studies claimed that task representation is carried out by the activated long-term memory portion of working memory (WM; Meiran and Kessler in J Exp Psychol Human Per8cept Perform 34:137–157, 2008). The present study provides a more direct support for this hypothesis. We used the reaction-time task-rule congruency effect (RT-TRCE) in a task-switching setup, and tested the effects of loading WM with irrelevant task rules on RT-TRCE. Experiment 1 manipulated WM load in a between-subject design. WM participants performed a color/shape task switching, while having 0, 1 or 3 numerical task rules as WM load. Experiment 2 used a similar load manipulation (1 or 3 rules to load WM) in a within-subject design. Experiment 3 extended these results by loading WM with perceptual tasks that were more similar to the shape/color tasks. The results show that RT-TRCE was not affected by WM load supporting the activated long-term memory hypothesis.

Introduction

The ability to handle several tasks in parallel, and to frequently switch among them according to external demands and/or internal choice, is regarded as a hallmark of cognitive control. Researchers still debate over the basic mechanisms that are related to task-switching phenomena, as well as over the origins of the substantial behavioral costs related to task switching. However, it is fairly agreed that task switching is not a monolithic mental ability, but rather relies on multiple cognitive processes. These may include, among others, task-set reconfiguration (Meiran, 1996), release from proactive interference (Allport, Styles, & Hsieh, 1994; Altmann & Gray, 2008), backward inhibition (Mayr & Keele, 2000), goal shifting and rule activation (Rubinstein, Meyer, & Evans, 2001), retrieval from long-term memory (LTM; Mayr & Kliegl, 2000) and so forth. One of the challenges of theories explaining task-switching behavior is to relate these processes to well-established mental structures to understand the way in which task switching is implemented within the cognitive architecture. This study focuses on the relations between task switching and working memory (WM).

WM is composed of transient stores of information and of the mental processes that are required to maintain and manipulate that information (Baddeley & Hitch, 1974; Miyake & Shah, 1999). As opposed to long-term memory that holds relatively stable representations, WM is a flexible system; such flexibility is required in task-switching experiments, where goal-relevant information as well as task rules change from one trial to the next. In task-switching experiments, the participants are usually required to respond to one stimulus at a time, using the rules of the currently relevant task. The experimental setup involves more than one task, and the participants are required to alternate between the tasks in a random or known order. Therefore, they have to keep track of the relevant task (goal) and to apply its rules to respond correctly. Previous studies looked at the involvement of WM in specific components of task-switching behavior. WM was found to

Y. Kessler · N. Meiran
Department of Psychology,
Ben-Gurion University of the Negev,
84105 Beer-Sheva, Israel

Y. Kessler (✉)
Rotman Research Institute,
Baycrest Centre for Geriatric Health,
3560 Bathurst St, Toronto, ON M6A 2E1, Canada
e-mail: ykessler@rotman-baycrest.on.ca

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keep track of the relevant task identity in situations, where there was no or little external cueing indicating which task to perform (Baddeley, Chincotta, & Adlam, 2001; Bryck & Mayr, 2005; Emerson & Miyake, 2003; Miyake, Emerson, Padilla, & Ahn, 2004; Saeki & Saito, 2004). Other studies looked at the relations between WM load, namely the amount of information held in WM, and task-switching cost, namely the performance difference between task-switch trials and task-repetition trials. Although manipulations of WM load did not affect the size of task-switching cost (Liefooghe, Barrouillet, Vandierendonck, & Camos, 2008; Logan, 2004), the number of task switches impeded the maintenance of information in WM (Liefooghe et al., 2008). These findings provide some evidence supporting a relation between WM and task switching.

The present study focuses on the reaction-time task-rule congruency effect (RT-TRCE) that is consistently found in task-switching experiments (see Meiran & Kessler, 2008, for review). This phenomenon reflects faster responses to stimuli for which the competing tasks indicate the same response, as compared to stimuli for which the competing tasks indicate different responses. The RT-TRCE reflects the fact that the execution of the relevant task is influenced, to some degree, by the rules of the irrelevant task. Because the rules of the irrelevant task are still highly accessible, as indicated by the existence of RT-TRCE, they have to be in WM along with the rules of the relevant task. It should be noted at this point that our line of reasoning in this paper, as well as in Meiran and Kessler (2008) refers to RT-TRCE only. Although TRCE is also observed in accuracy data, it arguably reflects a different mechanism. Specifically, TRCE in error proportion (PE-TRCE) stems from applying the wrong task rules (Meiran & Daichman, 2005; Meiran & Kessler, 2008; Yehene, Meiran, & Soroker, 2005).

To account for RT-TRCE, Meiran and Kessler (2008) built on a distinction between levels of representation within WM (Cowan, 1988, 1999; Oberauer, 2001, 2002). According to this view, WM is composed of the activated representations of LTM. The activated part of LTM has a relatively large capacity, and accordingly can hold information for relatively long periods of time, at least in the range of seconds to few minutes (Oberauer, 2001; Woltz & Was, 2007). A subset of the items in the activated LTM is held in a more capacity-limited mode of representation, namely the focus of attention (FOA). Although theorists still argue whether FOA limited to several items or to one object only (see Verhaeghen, Cerella, & Basak, 2004, for review), this debate is irrelevant for our present line of reasoning. To avoid confusion, we will use the term WM to address the whole concentric structure involving both the activated LTM and the FOA. These structures will be also referred to as the (relatively) capacity-unlimited and capacity-limited components, respectively.

Meiran and Kessler (2008) argued that RT-TRCE reflects response-category codes in activated LTM. The logic of this hypothesis is that due to the severe limitations of FOA, the task rules may be held in it only when the tasks are extremely simple. When task information exceeds the capacity of FOA, FOA must rely on information held in activated LTM. To support this claim, Meiran and Kessler showed that RT-TRCE depended on the existence of such category codes in LTM, and, therefore, was not observed using novel categories. To show that it was the LTM representation that was involved, Meiran and Kessler further showed that the RT-TRCE was found even for novel categories, if these categories were practiced beforehand, so that there was opportunity for LTM representations to form.

A key argument in this reasoning was that RT-TRCE does not stem from the limited-capacity portion of WM (FOA). This claim was partly based on a recent study by Kiesel, Wendt, and Peters (2007) that addressed this issue. Participants in that study had to alternate between magnitude and parity tasks performed on single digit stimuli. To observe RT-TRCE, the same set of keys served in both tasks (i.e., a bivalent response setup was used). Each trial consisted of a presentation of low or high memory load (2 or 5 letters, respectively), followed by two numerical judgment tasks. Both tasks were cued, and the second always involved a task switch (i.e., if the first task was magnitude then the second was parity, or vice versa). WM load was found to affect task performance, but importantly did not interact with RT-TRCE. Kiesel et al. concluded that the FOA does not mediate task-switching performance by maintaining all the abstract response categories. Rather, RT-TRCE reflects automatic activation of S–R associations held independently of capacity limitations. The latter claim was also supported by larger RT-TRCE for stimuli that were presented frequently in the context of the irrelevant task (Kiesel et al., 2007, Experiment 2; Wendt & Kiesel, 2008).

The present experiments were designed to further examine the involvement of the components of WM in maintaining irrelevant task information. Although Kiesel et al. showed that WM load did not influence the RT-TRCE, it is conceivable that such an interaction was not found due to their specific manipulation of load. Accordingly, there may be three alternative accounts to their results: (1) Because the effect of WM load on performance is non-linear (Baddeley & Hitch, 1974), the load caused by five letters could have been too small to detect an interaction with RT-TRCE. Evidence supporting the plausibility of this claim was recently reported by Ellenbogen and Meiran (2008), who showed an influence of high load on performance in the absence of influence with intermediate load; (2) only two letters were used for the smaller load condition, and five letters for the larger load condition. This could have led to memory-aiding strategies such as chunking or unitizing that decrease WM load; and most importantly (3) it might be that abstract task representations and letters tap different WM stores. Accordingly, it might be that both WM for items (letters) and WM for abstract response categories are capacity-limited, although not relying on shared resources (see Ellenbogen & Meiran, 2008, for a similar argument). This possibility is emphasized by a recent distinction between declarative and procedural WM (Oberauer, 2009). According to this view, separate and independent capacity limitations exist for procedural information (such as task rules) and for declarative information (such as letters). Therefore, manipulating the load of the declarative system may not affect the RT-TRCE due to a structural independence of the two WM systems.

This claim is further supported by a recent study by Duncan et al. (2008), which focused on goal neglect. In this paradigm, participants usually fail to perform parts of the instructed tasks, although they are fully able to describe it verbally. Importantly, the tendency to neglect parts of the goal increased when loading WM with additional task rules. Although simple declarative load was not manipulated in their study, Duncan et al. claimed that increasing the task complexity by adding task rules and requirements is very effective in increasing the competition between task components. By this logic, WM with extra tasks (but not extra non-relevant declarative information) might affect RT-TRCE if central, limited-capacity mechanisms are involved in the selection of the relevant task.

Because the lack of interaction between RT-TRCE and WM load is essentially a null effect, conclusive evidence is required to support it. The present study provides such evidence using an improved statistical power, and by loading WM with task rules rather then with verbal information. In all the experiments, participants switched between shape and color judgments of colored shapes, under different load conditions. Experiment 1 compared between a No-Load condition that involved the shape and color tasks only, a Univalent-Load condition that involved, in addition, numerical stimuli for which one numerical task had to be applied, and a Trivalent-Load condition involved numerical stimuli for which three tasks could have been applied, and for which the relevant task was randomly assigned in every trial. Note that we used completely different stimuli for the load task to ensure that whatever effect we find is not due to task confusion of any sort between the load tasks and the core tasks. Experiment 2 replicated these finding using the Univalent and Trivalent-Load conditions in a within-subject design. Experiment 3 was modeled after Experiment 2, but used perceptual loading tasks rather than numeric tasks. In each experiment, the RT-TRCE between the shape and color tasks was compared among the load conditions.

Experiment 1

Method

Participants

Seventy-five students participated in the experiment, for partial course credit or a payment of 20 NIS (about 5 $US). All the participants reported having normal or corrected to normal vision, and not having been diagnosed as suffering from learning disabilities. The participants were randomly assigned to the 3 experimental groups, 25 in each group. Seven participants were replaced (2 in the No-Load group, 2 in the Univalent-Load group and 3 in the Trivalent-Load group) due to using load-reduction strategies, in which they remembered only part of the S–R rules required. Specifically, in the post experimental debriefing, these participants reported that they remembered the S–R rules corresponding to one of the response keys only. When these rules were not fulfilled, they inferred that the other key has to be pressed. Because these strategies likely reduce WM load, these participants were replaced.

Apparatus and stimuli

The experiment was run on Pentium 4 computers with 17″ monitors. The software was programmed in E-Prime (Schneider, Eschman, & Zuccolotto, 2002). In each trial of the primary tasks, the stimulus was a circle (dimensions 4.58° × 4.58° in visual angle, assuming a 60-cm viewing distance) or a triangle (dimensions 5.44° × 5.44°), colored in red or blue. In each trial of the load tasks, the stimulus was one of the digits between 1 and 9, excluding 5 (height 1.72° × 1.14° width in visual angle, approximately), colored in white. The Hebrew words for "shape" and "color" were used as task cues for the primary tasks, where the Hebrew words for "magnitude", "distance" and "parity" were used as task cues for the load tasks. In each trial, a task cue was presented in white color above the stimulus that was presented in the middle of the screen. All the stimuli were presented with a black background.

Procedure

Three experimental groups differed in the amount of concurrent WM load necessary to perform the experiment. The No-Load group switched between the two primary tasks that required a classification of the stimuli according to their shape or color. The Univalent-Load group had, in addition, a numerical task that appeared in 25% of the trials. Each participant in the Univalent-Load group had to perform only one numerical tasks, being either a magnitude decision (whether the digit stimuli is smaller or larger than

5), a parity decision (whether the digit is odd or even) or a distance decision (whether the digit is close to 5, such as 3, 4, 6 and 7, or distant from 5, such as 1, 2, 8 and 9). The numerical tasks were counterbalanced between the subjects in the Univalent-Load group. In the Trivalent-Load group, all the above numerical tasks appeared in 25% of the trials, with equal probabilities.

The experiment began with 24 warm-up trials, followed by 4 blocks of 80 trials each. Each trial began with an empty screen that appeared for 1,000 ms. Then, the task cue appeared for either a short (100 ms) or long (1,000 ms) cue-target interval (CTI). Then, the target was presented along with the task cue, until a response was indicated.

The participants responded with their right and left index fingers, using the keys “a” (left) and “l” (right) in a standard QWERTY keyboard. For the shape task, the “l” key indicated circle and “a” indicated triangle. For the color task, the “l” key indicated red and “a” indicated blue. For the numerical tasks, the “l” key indicated small, odd or close to 5, for the magnitude, parity and distance tasks, respectively. The “a” key indicated large, even or distant from 5, respectively. The experiment was conducted in a single 20–30-min session.

Design and analysis

The core analysis compared the task-switching performance in the primary tasks, among the three experimental groups. An analysis of variance (ANOVA) was conduced involving Load as a between-subject variable and Task-Switch (switch, repeat), CTI (short, long), Congruency (congruent, incongruent) and Response-Repetition (same response key or a different response key relative to the preceding trial) as within-subject variables. The inclusion of CTI and Response-Repetition was done to examine the existence of standard task-switching effects (specifically, two-way interactions between Task-Switch and CTI and between Task-Switch and Response-Repetition), as well as high-order interactions involving Congruency. The analysis was performed on the shape and color tasks RT and error proportion (PE), separately, with the restriction that only trials that followed shape and color task trials were entered to this analysis. Responses faster than 100 ms or slower than 4,000 ms, as well as error trials and trials that followed an error did not enter the RT analysis. Alpha was 0.05 in all the analyses.

Results

Manipulation check

Before turning to the core analysis, we examined whether the loading conditions differed in their difficulty. To this end, we analyzed the loading tasks (i.e., the numerical tasks) data, by comparing RT and PE between the two load groups (univalent and trivalent). RTs were 904 and 1,486 ms for the Univalent- and Trivalent-Load groups, respectively, $F(1,48) = 49.05$, MSe = 86,293.19, $\eta_p^2 = 51$. PEs were 4 and 12%, respectively, $F(1,48) = 9.20$, MSe = 0.0080, $\eta_p^2 = 0.16$. These findings indicate a marked difficulty difference between the two load groups involved.

Core analyses

The following analyses were conducted on the shape and color tasks only. The full RT and PE data are presented in Appendix.

RT

We will begin with the most relevant findings, followed by the full ANOVA results. First, a main effect for Load was not observed, $F(2,72) = 0.10$, MSe = 650,306.48, $\eta_p^2 = 0.00$, $P = 0.91$. Moreover, no significant interaction was found between Load and any of the other variables. Especially, the two-way interaction between Congruency and Load was clearly non-significant, $F(2,72) = 0.41$, MSe = 29,952.22, $\eta_p^2 = 0.01$, $P = 0.67$. The RT-TRCE was 89, 75 and 67 ms for the No-Load, Univalent-Load and Trivalent-Load groups, respectively (see Table 1). Apparently, there was a numerical trend indicating smaller RT-TRCE with increasing load. Nonetheless, a linear trend analysis, which increases the statistical power of the comparison indicated a clearly non-significant effect, $F(1,72) = 0.79$, MSe = 29,952.22, $\eta_p^2 = 0.01$, $P = 0.38$. As seen, the effect, aside from being non-significant, was trivially small. The RT-TRCE was significant in all the groups, $F(1,72) = 26.26$, MSe = 29,952.22, $\eta_p^2 = 0.27$ for the No-Load group, $F(1,72) = 18.68$, MSe = 29,952.22, $\eta_p^2 = 0.21$ for the Univalent-Load group and $F(1,72) = 14.93$, MSe = 29,952.22, $\eta_p^2 = 0.17$ for the

Table 1 Congruency effects by Load in Experiments 1 and 2

	Experiment 1			Experiment 2	
	No load	Univalent load	Trivalent load	Univalent load	Trivalent load
Incongruent	**988**	**956**	**967**	**1,032**	**1,045**
	(0.07)	(0.05)	(0.06)	(0.03)	(0.04)
Congruent	**899**	**881**	**900**	**978**	**988**
	(0.02)	(0.03)	(0.02)	(0.01)	(0.01)
Congruency effect	**89**	**75**	**67**	**55**	**57**
	(0.04)	(0.03)	(0.04)	(0.02)	(0.03)

Mean RTs appear in bold, mean PEs appear in parentheses

Trivalent-Load group. None of the high-order interactions involving these two variables was significant.

In addition to the effects discussed above, main effects were found for Task-Switch, $F(1,72) = 136.92$, MSe = 66,020.02, $\eta_p^2 = 0.66$, CTI, $F(1,72) = 200.86$, MSe = 61,510.52, $\eta_p^2 = 0.74$ and Congruency, $F(1,72) = 59.06$, MSe = 29,952.22, $\eta_p^2 = 45$. Two-way interactions were found for Task-Switch and CTI, $F(1,72) = 43.98$, MSe = 24,441.87, $\eta_p^2 = 0.38$, Task-Switch and Congruency, $F(1,72) = 5.41$, MSe = 23,091.60, $\eta_p^2 = 0.07$ and Task-Switch and Response-Repetition, $F(1,72) = 52.97$, MSe = 38,985.43, $\eta_p^2 = 42$. Three-way interactions were found between Task-Switch, CTI and Response-Repetition, $F(1,72) = 7.35$, MSe = 25,424.33, $\eta_p^2 = 0.09$ and between CTI, Congruency and Response-Repetition, $F(1,72) = 4.10$, MSe = 14,398.12, $\eta_p^2 = 0.05$.

PE

The main effects of Load, as well as the two-way interaction between Load and Congruency, were clearly nonsignificant, $F(2,72) = 0.15$, MSe = 0.0404, $\eta_p^2 < 0.01$, $P = 0.86$ and $F(2,72) = 1.02$, MSe = 0.0092, $\eta_p^2 = 0.03$, $P = 0.37$, respectively. The latter result reflects a PE-TRCE of 4, 3 and 4% for the No-Load, Univalent-Load and Trivalent-Load, respectively.

Main effects were found for Task-Switch, $F(1,72) = 56.38$, MSe = 0.0038, $\eta_p^2 = 0.44$, CTI, $F(1,72) = 6.22$, MSe = 0.0034, $\eta_p^2 = 0.08$, Congruency, $F(1,72) = 42.44$, MSe = 0.0092, $\eta_p^2 = 0.37$ and Response-Repetition, $F(1,72) = 7.59$, MSe = 0.0033, $\eta_p^2 = 0.10$. Two-way interactions were found between Task-Switch and CTI, $F(1,72) = 6.14$, MSe = 0.0036, $\eta_p^2 = 0.08$, Task-Switch and Congruency, $F(1,72) = 16.95$, MSe = 0.0031, $\eta_p^2 = 0.19$ and Task-Switch and Response-Repetition, $F(1,72) = 15.18$, MSe = 0.0035, $\eta_p^2 = 0.17$.

Discussion

The results of Experiment 1 support the hypothesis that RT-TRCE does not stem from the limited portion of WM, and therefore, is relatively immune from WM load manipulations. To obtain a clearer picture of the effects of load on RT-TRCE, we conducted Experiment 2, which used a similar paradigm in a within-subject design, affording enhanced statistical power. Another important advantage of the within subjects design is that the same subjects are compared. Therefore, this design prevents the problem of subject sample differences found in between-subject designs.

Experiment 2

Method

Participants

Twenty-four students participated in the experiment, for partial course credit or a payment of 20 NIS (about 5 $US). All the participants reported having normal or corrected to normal vision, and not having been diagnosed as suffering from learning disabilities. Two participants were removed from the analysis due to exceptionally high error rates: 28% in the primary tasks, and 45% in the numerical tasks in the Trivalent-Load condition, respectively. Accordingly, the analysis was conducted with the remaining 22 participants.

Apparatus and stimuli

The apparatus and stimuli were identical to those used in Experiment 1.

Procedure

Each participant performed both the Univalent-Load and the Trivalent-Load conditions. The No-Load condition of Experiment 1 was omitted to simplify the design. The conditions were blocked. The order of the blocks was Univalent-Trivalent-Trivalent-Univalent for half of the participants, and Trivalent-Univalent-Univalent-Trivalent for the other half of the participants. A short practice phase of 20 trials appeared before the first univalent block, and a short practice phase of 60 trials appeared before the first trivalent block. Each block involved 5 runs of 40 trials each.

We used separate response keys for the two tasks. The keys “z”, “x”, “.”and “/” in a standard QWERTY keyboard were used. The participants were asked to place the index and middle fingers of each hand on the keys. For half of the participants, the right hand served for the numerical tasks and the left hand served for the shape/color tasks. This assignment was reversed among the other half of the participants. The rightmost among the keys related to the numerical tasks indicated odd, distant from 5, and small, for the parity, distance and magnitude tasks, respectively. The leftmost among the numerical response keys indicated even, close to 5 and large, respectively. The rightmost among the shape/color task keys indicated red and triangle, for the color and shape tasks, respectively. The leftmost among the shape/color tasks indicated blue and circle, respectively. The task order and key mappings were counterbalanced across the participants. The experiment was conducted in a single 1-h session.

Design and analysis

An ANOVA was conducted with Load (Univalent, Trivalent), Task-Switch, Congruency, CTI, and Response-Repetition as within-subject variables. Trial exclusion criteria were the same as in Experiment 1.

Results

Manipulation check

Reaction times in the numeric tasks were 1,000 and 1,471 ms for the Univalent and Trivalent conditions, respectively, $F(1,21) = 78.35$, MSe = 31,130.25, $\eta_p^2 = 79$. PEs were 2 and 4%, respectively, $F(1,21) = 11.54$, MSe = 0.0004, $\eta_p^2 = 0.35$. These findings indicate a difficulty difference between the two load conditions.

Core analyses

The full RT and PE data are presented in Appendix.

RT

The main effect of Load was non-significant, $F(1,21) = 0.24$, MSe = 94,297.99, $\eta_p^2 = 0.01$, $P = 0.63$. Also, the two-way interaction between Load and Congruency was clearly non-significant, $F(1,21) = 0.01$, MSe = 20,347.77, $\eta_p^2 < 0.01$, $P = 0.91$. The RT-TRCE was 55 and 57 ms in the Univalent and Trivalent-Load conditions, respectively (see Table 1). No high-order interactions involving Load were significant. As in Experiment 1, RT-TRCE was unaffected by WM load.

In addition, main effects were found for Task-Switch, $F(1,21) = 29.97$, MSe = 188,667.67, $\eta_p^2 = 0.59$, CTI, $F(1,21) = 77.01$, MSe = 71,580.68, $\eta_p^2 = 0.79$ and Congruency, $F(1,21) = 26.08$, MSe = 20,940.87, $\eta_p^2 = 0.55$. Two-way interactions were found between Task-Switch and CTI, $F(1,21) = 7.75$, MSe = 31,596.98, $\eta_p^2 = 0.27$, Task-Switch and Congruency, $F(1,21) = 5.71$, MSe = 17,646.05, $\eta_p^2 = 0.21$, Task-Switch and Response-Repetition, $F(1,21) = 22.48$, MSe = 35,074.95, $\eta_p^2 = 0.52$ and Congruency and Response-Repetition, $F(1,21) = 6.48$, MSe = 18,343.84, $\eta_p^2 = 0.24$. Finally, three-way interactions were found between Task-Switch, CTI and Response-Repetition, $F(1,21) = 10.32$, MSe = 29,977.26, $\eta_p^2 = 0.33$ and between Task-Switch, Congruency and Response-Repetition, $F(1,21) = 10.60$, MSe = 18,819.26, $\eta_p^2 = 0.34$.

PE

The main effect of Load was non-significant, $F(1,21) = 1.07$, MSe = 0.0049, $\eta_p^2 = 0.05$, $P = 0.31$. Other main effects were found for Task-Switch, $F(1,21) = 14.19$, MSe = 0.0039, $\eta_p^2 = 0.40$, Congruency, $F(1,21) = 25.11$, MSe = 0.0033, $\eta_p^2 = 0.54$ and Response-Repetition, $F(1,21) = 6.85$, MSe = 0.0022, $\eta_p^2 = 0.25$. The main effect for CTI was just significant, $F(1,21) = 4.15$, MSe = 0.0012, $\eta_p^2 = 0.17$, $P = 0.05$. Two-way interactions were found between Task-Switch and Response-Repetition, $F(1,21) = 19.76$, MSe = 0.0011, $\eta_p^2 = 0.48$, and between Task-Switch and Congruency, $F(1,21) = 14.31$, MSe = 0.0022, $\eta_p^2 = 0.41$. Finally, the three-way interaction between Load, CTI and Response-Repetition was significant, $F(1,21) = 4.41$, MSe = 0.0010, $\eta_p^2 = 0.17$.

Discussion

The results of Experiments 1 and 2 provide converging evidence supporting our main hypothesis that the RT-TRCE stems from relatively capacity-unlimited activated LTM, and, hence is not diminished by WM load. However, an alternative account for our data would also predict this pattern of results. According to this account, WM capacity limitations are content specific. For example, while our primary tasks were perceptual in nature, involving color and shape decisions (and hence the ventral visual stream), the loading tasks used in Experiments 1 and 2 involved declarative semantic memory. Therefore, it is plausible that within each of these domains the tasks are maintained in a capacity-limited medium, but these two limitations are mutually independent. One feature of our data may support this prediction. Specifically, although marked effects of load were observed in the loading tasks' data (namely, in the numerical tasks), these effects were not observed in the performance in the shape and color tasks.

Accordingly, two alternative accounts can explain our results. According to the first, task representations are maintained in a single activated LTM store. Because its capacity is relatively unlimited, adding more tasks does not lead to any degradation in performance, as long as the loaded tasks are irrelevant for the present stimuli. According to the second alternative, WM is composed of highly content-specific modules, and task representation requires capacity in each of them. However, loading WM with more tasks did not affect the overall performance or the RT-TRCE in the previous experiments, because the loaded tasks used a different WM module.

Experiment 3 was designed to distinguish between the aforementioned alternatives. The design of this experiment was modeled after Experiment 2, but the loading tasks were created to be conceptually close to the stimuli of the shape and color tasks. Specifically, we used visual figures of clover that were judged on three perceptual dimensions: size, fill and line thickness. Accordingly, all the tasks in the experiment required the same type of perceptual judgment, and, hence, should depend on a single WM mechanism. This is unlike the situation in Experiments 1 and 2, where the core tasks required perceptual categorization, while the numeric loading tasks required semantic processing. In Experiment 3, it is conceivable that the same WM component was used for perceptual processing of both the core and loading stimuli. It should be noted that the clover figures were completely different from the shapes used in the shape and color tasks, so as to prevent crosstalk between the core and the load tasks.

Experiment 3

Method

Participants

Twenty-four students participated in the experiment, for partial course credit. All the participants reported having normal or corrected to normal vision, and not having been diagnosed as suffering from learning disabilities.

Apparatus and stimuli

The apparatus was identical to that used in Experiments 1 and 2. The stimuli for the color and shape tasks were also identical. New stimuli were created for the loading tasks. Specifically, eight figures of clover were created from a combination of three orthogonal dimensions: size (small or large), fill (dots or squares) and line thickness (thin or thick). The small figures subtended 3.8° (height) $\times$ 3.4° (width) in visual angle, assuming a 60-cm viewing distance, and the large figures subtended 5.2° $\times$ 4.8°, respectively. The Hebrew words for “size”, “fill” and “thickness” served as task cues for the loading tasks.

Procedure

The procedure and design were identical to these of Experiment 2, except for using visual tasks (size, fill and thickness) as the loading tasks instead of the numerical tasks used in Experiment 2. For half of the participants, the right hand served for the numerical tasks and the left hand served for the shape/color tasks. This assignment was reversed among the other half of the participants. The rightmost among the keys related to the loading tasks indicated small, thin and dots, for the size, thickness and fill tasks, respectively. The leftmost among the numerical response keys indicated large, thick and squares, respectively.

Results

Manipulation check

Reaction times in the numeric tasks were 704 and 896 ms for the Univalent and Trivalent conditions, respectively, $F(1,23) = 70.10$, MSe = 6,316.17, $\eta_p^2 = 75$. PEs were 3 and 4%, respectively, but did not differ significantly, $F(1,23) = 1.84$, MSe = 0.0005, $\eta_p^2 = 0.07$. Accordingly, the difficulty difference between the load conditions was established.

Core analyses

The full RT and PE data are presented in Appendix.

RT

The main effect of Load was non-significant, $F(1,23) = 0.24$, MSe = 92,319.79, $\eta_p^2 = 0.01$, $P = 0.63$. As before, the two-way interaction between Load and Congruency was clearly non-significant, $F(1,23) = 0.28$, MSe = 24,104.21, $\eta_p^2 = 0.01$, $P = 0.60$. However, the three-way interaction between Load, Congruency and CTI was significant, $F(1,23) = 7.53$, MSe = 12,398.90, $\eta_p^2 = 0.25$ (see Fig. 1). To examine this interaction, we looked at the simple interaction between Load and Congruency in each CTI. In the short CTI, there was not effect of load on congruency, $F(1,23) = 1.49$, MSe = 16,779.18, $\eta_p^2 = 0.06$, $P = 0.23$. In the long CTI, however, the simple interaction was marginally significant, $F(1,23) = 3.81$, MSe = 19.723.93, $\eta_p^2 = 0.14$, $P = 0.06$. Specifically, the congruency effect was larger in the Trivalent-Load condition (111 ms) than in the Univalent-Load condition (60 ms). Although this interaction was admittedly not predicted, it further supports our main hypothesis. Not only that the congruency effect is not diminished by load, but may even increase with load in longer CTIs. At present, it is still premature to hypothesize about the origin of this effect, especially, since it was not observed in the previous experiments. No other interactions involving Load were significant.

In addition, main effects were found for Task-Switch, $F(1,23) = 88.63$, MSe = 47,605.85, $\eta_p^2 = 0.79$, CTI, $F(1,23) = 284.87$, MSe = 28,784.89, $\eta_p^2 = 0.93$ and Congruency, $F(1,23) = 60.85$, MSe = 24,439.79, $\eta_p^2 = 0.73$. Two-way interactions were found between Task-Switch and CTI, $F(1,23) = 12.54$, MSe = 15,409.29, $\eta_p^2 = 0.35$, Task-Switch and Congruency, $F(1,23) = 7.36$, MSe = 26,299.00, $\eta_p^2 = 0.24$, Task-Switch and Response-Repetition, $F(1,23) = 27.25$, MSe = 32,266.02, $\eta_p^2 = 0.54$ and Congruency and Response-Repetition, $F(1,23) = 6.07$, MSe = 13,778.30, $\eta_p^2 = 0.21$. Finally, additional three-way interactions were

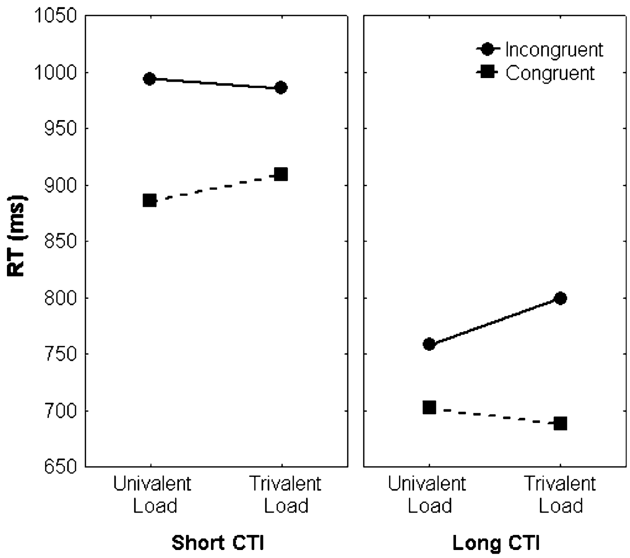

Fig. 1 Mean RT as a function of CTI, Load and Congruency in Experiment 3

found between Task-Switch, CTI and Response-Repetition, $F(1,23) = 17.47$, $\text{MSe} = 22{,}495.48$, $\eta_p^2 = 0.43$ and between Task-Switch, Congruency and Response-Repetition, $F(1,23) = 4.44$, $\text{MSe} = 15{,}933.71$, $\eta_p^2 = 0.16$.

PE

The main effect of Load was non-significant, $F(1,23) = 0.30$, $\text{MSe} = 0.0099$, $\eta_p^2 = 0.01$, $P = 0.59$. Main effects were found for Task-Switch, $F(1,23) = 44.27$, $\text{MSe} = 0.0095$, $\eta_p^2 = 0.66$, Congruency, $F(1,23) = 47.85$, $\text{MSe} = 0.0159$, $\eta_p^2 = 0.68$, CTI, $F(1,23) = 6.05$, $\text{MSe} = 0.0047$, $\eta_p^2 = 0.21$ and Response-Repetition, $F(1,23) = 10.77$, $\text{MSe} = 0.0049$, $\eta_p^2 = 0.32$. Two-way interactions were found between Task-Switch and CTI, $F(1,23) = 5.78$, $\text{MSe} = 0.0036$, $\eta_p^2 = 0.20$, Task-Switch and Response-Repetition, $F(1,23) = 22.15$, $\text{MSe} = 0.0035$, $\eta_p^2 = 0.49$ and Task-Switch and Congruency, $F(1,23) = 35.88$, $\text{MSe} = 0.0034$, $\eta_p^2 = 0.61$. Finally, the three-way interaction between Task-Switch, CTI and Response-Repetition was significant, $F(1,23) = 8.63$, $\text{MSe} = 0.0031$, $\eta_p^2 = 0.27$.

Discussion

The results of Experiment 3 are very similar to those of the previous experiments. Although load affected the performance of the loading tasks, it did not affect the performance of the color and shape tasks. The finding of an over-additive interaction between load and congruency in the long CTI was only marginally significant, but more importantly idiosyncratic. However, although unexplained, the direction of this effect does not undermine our hypothesis that the RT-TRCE was not reduced by load.

This pattern of results clearly speaks in favor of our above first alternative claiming that the results of Experiments 1 and 2 did not stem from using different WM stores for the core and loading tasks. Even when using very similar perceptual judgments, task representation is unaffected by the amount of WM load.

General discussion

The present study provided relatively direct evidence supporting the claim that, at least when task information load is not trivial, task representation is not carried out by a limited-capacity portion of WM, the FOA. In Experiment 1, using a between-subjects design RT-TRCE was unaffected by task load. Experiment 2, using a within-subject design with improved statistical power and experimental control, reached to the same conclusions. Experiment 3 used an even more restricting criterion of loading WM with tasks that had very similar properties to the tasks used to measure RT-TRCE. Again, there was no evidence any load-dependent decrement in performance.

The mere existence of RT-TRCE indicates that although only one task is ultimately selected for action, the selection process is based on a graded task representation. Accordingly, all the tasks in the experimental context are activated to some degree, even if they are currently irrelevant. This gradual selection mechanism, as opposed to all-or-none selection, is arguably preferable in task-switching situations, where the cognitive system has to perform one task while being prepared to perform other tasks in the immediately following the trial (Goschke, 2000; Meiran, Kessler, & Adi-Japha, 2008). However, the drawback of such a graded selection mechanism is seen by the effect of irrelevant tasks on performance in conflict situations, namely incongruent trials. Had the relevant task been selected in an all-or-none fashion, the irrelevant tasks would not have affected performance at all. Simultaneous maintenance of graded task representations must be carried out by a portion of WM which is not severely restricted in capacity for the simple fact that the amount of information usually exceeds the capacity limitations of FOA. We, therefore, hypothesized that the activated LTM, which is composed of relatively long-lasting activation of information, hosts task representation. Accordingly, RT-TRCE reflects interference between task representations in the activated LTM (Meiran & Kessler, 2008).

Interestingly, two recent studies conducted in our laboratory found that increasing WM load resulted in diminishing two effects that are related to RT-TRCE, backward compatibility (Ellenbogen & Meiran, 2008) and first-trial flanker compatibility (Cohen-Kdoshay & Meiran, 2007). We will turn to discuss each of these studies separately.

The effect of WM load on backward compatibility

The backward compatibility effect (Hommel, 1998) is observed in situations where processing of two tasks overlap in time. In a typical backward compatibility experiment, participants are required to perform two tasks, each corresponding to a different stimulus. The stimuli are presented simultaneously, or in close temporal proximity, so their processing overlaps in time. Participants are instructed which task to perform first and which to perform second. The backward compatibility effect indicates faster responses to the first task, if they are compatible with the responses of the second task. For example, Hommel (1998) presented participants with colored letters, and instructed them to judge their color, and then their identity. Although the color judgment (red or green) was made using a keypress using the right or left hands, the identity judgment (H or S) was made by saying "red" or "green" in response to the letter identity. Hommel (1998) found that the response for the first color judgment was enhanced when it was compatible to the response of the second task. The existence of backward compatibility effect suggests that some aspects of the tasks are processed in parallel rather than serially.

Ellenbogen and Meiran (2008) built on an earlier work by Hommel and Eglau (2002) that investigated the involvement of WM in task representation. Using the backward compatibility paradigm as an index for the currently irrelevant task availability, Ellenbogen and Meiran manipulated the number of task rules composing the first task of the two. The backward compatibility effect was not affected by increasing the number of task rules from 2 to 4, but was diminished with six task rules. This result suggests that limited-capacity WM is involved in task representation in the dual-task paradigm.

The major difference between the dual-task paradigm and the task-switching paradigm is the temporal overlap between the processing stages of successive tasks. This overlap allows for simultaneous selection of the relevant rules in both tasks. Accordingly, two relevant response categories should be simultaneously active in WM—corresponding to the two tasks in hand. Backward compatibility refers to the degree in which these response categories are compatible. In contrast, in task-switching experiments, such the present study, the tasks are presented serially, so that only one response category was relevant in each time. RT-TRCE stems, therefore, from spontaneous activation of the irrelevant task's response categories. Meiran and Kessler (2008) claimed that the activated LTM is not sufficient to ensure correct task-switching performance, and a more restricted FOA should be used to ensure that the relevant (and thus more heavily biased) task is actually selected (see Meiran & Kessler, Fig. 3). Accordingly, RT-TRCE occurs between the activated LTM and the FOA, while backward compatibility might only occur within the FOA. Because the latter is strictly capacity-limited, backward compatibility (but not RT-TRCE) is sensitive to manipulating the number of task rules.

Another difference between our paradigm and this of Ellenbogen and Meiran should be noted. Ellenbogen and Meiran modeled their task after Hommel and Eglau (2002), who manipulated the number of task rules within a set of tasks. In contrast, in the present study, we manipulated WM load by adding a different, irrelevant set of tasks. Further research is required to determine whether this issue contributed to the differential results.

The effect of WM load on first-trial flanker effect

The flanker effect (Eriksen & Eriksen, 1974) reflects quicker and more accurate processing of a target stimulus when it is surrounded by irrelevant stimuli that are related to the same response as the target, as compared to situations where the irrelevant stimuli are related to a competing response. Cohen-Kdoshay and Meiran (2007, 2009) found that the flanker effect is evident immediately after the instructions were given, without responding to any of the stimuli yet. This finding was termed "first-trial flanker effect". Arguably, this effect reflects autonomous response activation of the irrelevant stimuli. Because this effect is observed when no previous encounter with the S–R rules was conducted, it is only based on the representation of the instructions in WM. To support the latter claim, Cohen-Kdoshay and Meiran (2007, Experiment 4) manipulated WM load by adding a secondary, loading go/no-go task that appeared occasionally, and involved different stimuli and a different task and response. As a result, the first-trial flanker effect was eliminated.

Although adding a single task was enough for diminishing the first-trial flanker effect, we claim that this finding was specific to a situation in which the response categories were novel. Indeed, Cohen-Kdoshay and Meiran used arbitrary rules such as letters from the beginning versus the end part of the alphabet. Response categories are created in LTM and can thus become a part of activated LTM through practice (Meiran & Kessler, 2008). Immediately after the instructions are given, it is very unlikely that activated LTM is already involved, but rather more fragile codes that are held in WM. Accordingly, adding more task rules loads WM to a point in which autonomic activation of irrelevant task rules cannot affect the processing of the relevant targets. Therefore, the findings of Cohen-Kdoshay and Meiran (2007) do not undermine our present conclusions.

Another relevant study is by Waszak, Wenke, and Brass (2008). The authors compared the RT-TRCE in two conditions. In one condition, the interfering rule has been applied beforehand. In the other condition, the interfering rule has not been applied beforehand, but only instructed. These authors found RT-TRCE for previously applied rules but not for rules which were instructed, but were not applied beforehand. This result seems to contrast with that of Cohen-Kdoshay and Meiran (2007, 2009). Yet, the current conception can potentially explain this apparent paradox. One core difference between the studies concerns the task information load. While in Cohen-Kdoshay and Meiran's studies, participants had to keep one category-response mapping rule in WM, in Waszak et al.'s study, they had to keep many category-response mapping rules in WM. This is especially true, since arbitrary response categories were used. Consequently, the amount of information exceeded the capacity limitations of FOA and the information had to be held in activated LTM. Thus, the conditions in Waszak et al.'s study resembled the high load condition in Cohen-Kdoshay and Meiran's study in which there was no first-trial flanker effect.

Note that precisely for these reasons we consistently found load effects in the load tasks, but not in the core shape–color tasks. According to our reasoning, because the task information (as well as the loading information) is held in activated LTM, it is not subjected to capacity limitation, which is why there was no load effect on the core tasks. The effect on the load tasks could be explained by the fact that the same set of stimuli cued one versus several tasks as well as by interference among the loading tasks.

Conclusions

The present study adds critical support to the hypothesis that in task switching, task representations are held in the activated LTM portion of WM. Previous support for the activated LTM hypothesis was provided by Kiesel et al. (2007) who showed no effects of WM load on the RT-TRCE. Meiran and Kessler (2008) further showed that RT-TRCE depends on using LTM-based categories. Kiesel et al.'s critical result is equivocal because it employed declarative WM load, while the task rules are presumably held in procedural WM (Oberauer, 2009). Using procedural load, the present results found again that load does not influence the RT-TRCE.

A final word of caution is required. It is tempting to regard the effects of WM load as dichotomous, namely to see whether there is an effect or not. However, we propose that the degree of sensitivity for load is a more adequate measure. For example, the results of Cohen-Kdoshay and Meiran (2007, 2009) showed high sensitivity for load, since only one loading task eliminated the first-trial flanker effect. Ellenbogen and Meiran (2008) showed a much weaker sensitivity for load, because backward compatibility was eliminated only when loading WM with six task rules. The results of our present study showed a yet smaller sensitivity for load. We cannot rule out the possibility that loading WM with more task rules would result in a reduced RT-TRCE. Nonetheless, we claim that such a result will not undermine our basic claim that activated LTM carries out task representation. With a very large number of loading tasks, even activated LTM may be affected. Still, within the range of 1–3 tasks, our results showed unequivocal evidence that RT-TRCE is resistant to load manipulations.

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Appendix

See Table 2.

Table 2 RT and PE means by condition, in Experiments 1–3

			Experiment 1			Experiment 2		Experiment 3	
			No Load	Univalent Load	Trivalent Load	Univalent Load	Trivalent Load	Univalent Load	Trivalent Load
Short CTI	Task Switch	Incongruent R-switch	**1104** (.13)	**1152** (.11)	**1143** (.07)	**1158** (.06)	**1185** (.07)	**1033** (.14)	**1026** (.18)
		Incongruent R-repeat	**1254** (.09)	**1244** (.06)	**1319** (.08)	**1261** (.03)	**1349** (.06)	**1158** (.11)	**1183** (.11)
		Congruent R-switch	**1038** (.07)	**1097** (.05)	**1100** (.05)	**1160** (.02)	**1169** (.03)	**937** (.09)	**972** (.07)
		Congruent R-repeat	**1105** (.01)	**1130** (.02)	**1115** (.03)	**1149** (.00)	**1226** (.00)	**961** (.02)	**996** (.03)
	Task Repetition	Incongruent R-switch	**1041** (.04)	**1004** (.04)	**985** (.03)	**1094** (.02)	**1064** (.02)	**973** (.07)	**925** (.03)
		Incongruent R-repeat	**950** (.06)	**850** (.03)	**874** (.05)	**959** (.01)	**945** (.03)	**811** (.07)	**807** (.06)
		Congruent R-switch	**935** (.01)	**961** (.01)	**957** (.02)	**1028** (.01)	**1055** (.00)	**885** (.01)	**917** (.01)
		Congruent R-repeat	**831** (.02)	**803** (.02)	**810** (.02)	**873** (.00)	**907** (.01)	**757** (.01)	**752** (.03)
Long CTI	Task Switch	Incongruent R-switch	**933** (.08)	**903** (.08)	**869** (.08)	**1035** (.05)	**968** (.05)	**819** (.13)	**854** (.13)
		Incongruent R-repeat	**966** (.06)	**940** (.04)	**980** (.07)	**1050** (.02)	**1112** (.04)	**826** (.12)	**894** (.10)
		Congruent R-switch	**825** (.04)	**770** (.03)	**869** (.03)	**954** (.01)	**984** (.03)	**775** (.03)	**730** (.04)
		Congruent R-repeat	**857** (.01)	**847** (.03)	**888** (.02)	**931** (.00)	**909** (.00)	**733** (.01)	**731** (.02)
	Task Repetition	Incongruent R-switch	**859** (.06)	**835** (.02)	**799** (.05)	**888** (.01)	**891** (.02)	**723** (.07)	**738** (.04)
		Incongruent R-repeat	**796** (.03)	**720** (.04)	**767** (.05)	**811** (.02)	**843** (.01)	**664** (.06)	**712** (.04)
		Congruent R-switch	**827** (.02)	**762** (.01)	**753** (.01)	**857** (.01)	**839** (.00)	**680** (.02)	**659** (.02)
		Congruent R-repeat	**775** (.02)	**679** (.04)	**711** (.01)	**868** (.02)	**813** (.00)	**621** (.01)	**631** (.02)

Mean RTs appear in bold, and mean PEs appear in parentheses. CTI Cue-Target Interval; R Response

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