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Component Processes in Task Switching

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Participants switched between two randomly ordered, two-choice reaction-time (RT) tasks, where an instructional cue preceded the target stimulus and indicated which task to execute. Task-switching cost dissipated passively while the participants waited for the instructional cue in order to know which task to execute (during the Response–Cue Interval). Switching cost was sharply reduced, but not abolished, when the participants actively prepared for the task switch in response to the instructional cue (during the Cue–Target Interval). The preparation for a task switch has shown not to be a by-product of general preparation by phasic alertness or predicting target onset. It is suggested that task-switching cost has at least three components reflecting (1) the passive dissipation of the previous task set, (2) the preparation of the new task set, and (3) a residual component.

Compared to the wealth of empirical evidence regarding elementary cognitive process, relatively little is known on how these processes are controlled (Logan, 1985; Monsell, 1996). One paradigm to study cognitive control is task switching, in which participants rapidly switch between two or more choice reaction-time (RT) tasks. In most circumstances, switching tasks is associated with a sizable decrement in performance (called *switching cost)* (Allport, Styles, & Hsieh, 1994; Biederman, 1972; de Jong, in press; Fagot, 1994; Gopher, Armony, & Greenshpan, in press; Jersild, 1927; Meiran, 1996; Rogers & Monsell, 1995; Rubinstein, Meyer, & Evans, submitted). Two explanations have been suggested for this cost. The first explanation is based on the concept of *preparatory reconfiguration,* presumably an organizational-executive process. The second explanation is based on the concept of *task set inertia,* a mechanism not necessarily related to executive processing.

According to some authors, at least part of task-switching cost reflects the *reconfiguration* of processing mode prior to task performance (de Jong, in

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press; Fagot 1994; Goschke, in press; Meiran 1996, in press-a, in press-b; Rogers & Monsell, 1995). Rubinstein et al. (submitted) suggested that reconfiguration is composed of two components. One is goal activation, presumably related to the updating of the contents of declarative memory where task demands are represented. The other component is rule activation, related to the activation of procedural memory aspects related to task performance. In contrast, Allport et al. (1994, see also Allport & Wylie, in press) emphasized processes that are *unrelated* to intentional control. They suggested ''that . . . the [task] switch cost. . . . reflects a kind of proactive interference from competing S-R mappings with the same stimuli, persisting from the instruction set on preceding trials. We [Allport et al.] might call this phenomenon task set inertia'' (p. 436).

Important evidence favoring the reconfiguration view comes from experiments showing that switching cost is reduced by increasing preparation. However, Allport et al. (1994) attributed the reduction in switching costs to passive dissipation of the task set from the previous trial rather than activation of the task set of the upcoming trial, as implied from the reconfiguration position. A relevant example is Allport et al.'s fifth experiment. In that experiment, the authors gave participants pairs of trials. They were either required to perform the same task in succession or perform one task in the first trial in the pair and perform another task in the second trial of the pair. Of interest were the responses in the second trial in the pair that required either task switching or task repetition. In order to manipulate preparation, Allport et al. varied the interval between the response given in the first trial in the pair and the presentation of the target stimulus in the second trial in the pair. Since the participants knew in advance if a task switch was required, they could prepare for the task switch during the Response–Target Interval. Surprisingly, a large increase in the Response–Target Interval was accompanied by a relatively modest decline in task-switching cost. According to Allport et al., ''The small reduction in [task] shift costs over delays of this order . . . accords with a limited task-set inertia dissipation over this time scale'' (p. 442). As explained below, a major problem with Allport et al.'s conclusion is that their experimental paradigm cannot distinguish unequivocally between passive dissipation of the previous task set on the one hand and limited preparatory reconfiguration on the other hand. This is also true for Rogers and Monsell's (1995) paradigm.

In the present work, we used a cueing paradigm (e.g., Biederman, 1972; de Jong, 1995, in press; Shaffer, 1965; Sudaven & Taylor, 1987) which makes it possible to assess separately preparatory reconfiguration and the dissipation of the previous task set. Our experimental paradigm was identical to that used by Meiran (1996). In his experiments (see Fig. 1), participants were required to identify the location of a target stimulus that was presented inside a 2 $\times$ 2 grid. Participants switched between two randomly ordered tasks: UP-DOWN, involving a discrimination of location along the vertical axis,

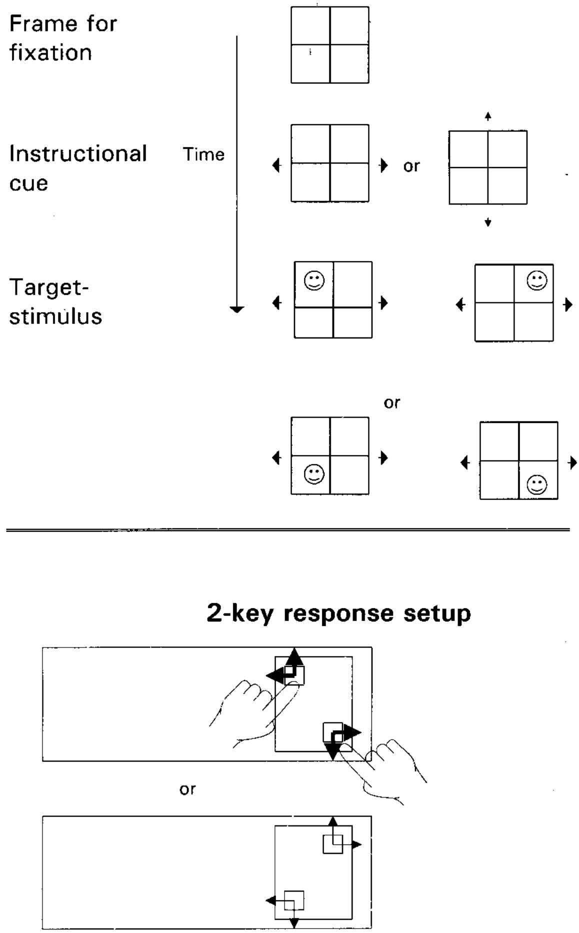

FIG. 1. The experimental paradigm.

and RIGHT-LEFT, involving discrimination of location along the horizontal axis. A series of events in a trial consisted of (1) an empty grid for fixation; (2) the presentation of the instructional cue, informing participants which task is next; and (3) the presentation of the target stimulus for response. In order to minimize memory load, the instructional cues were kept on the screen until the response (see Jersild, 1927; Spector & Biederman, 1976; Rubinstein et al., submitted, for the role of goal memory).

The most important independent variable in the paradigm was *Task-Switch*, which was defined in relation to the preceding trial. If the task was different in Trial N and Trial N−1, then Trial N was considered to be a *switch* condition. If the two trials involved the same task, the condition was considered to be a *no-switch* condition. The basic finding was that a switching of task was associated with a cost (switch RT > no-switch RT). In order to manipulate preparation, the instructional cues preceded the target stimulus at either a short (~100–250 ms) or a long (over 1500 ms) *Cue–Target Interval* (CTI). It was found that task-switching cost was considerably larger when CTI was short and participants did not have sufficient time to prepare as compared to when CTI was long and there was sufficient opportunity for preparation. While CTI reflects preparation time, set dissipation time is related to the interval separating the response on Trial N-1 and the presentation of the target stimulus in Trial N, the Response–Target Interval. Meiran demonstrated that preparation is involved in the reduction of switching cost by manipulating the CTI while keeping constant the Response–Target Interval. He either presented the instructional cue close in time to the response (thus far from the target, creating a long CTI) or far from the response, thus close in time to the target (short CTI). If the logic of the experiment is accepted, one must conclude that the only reason for the reduction in switching cost by CTI must have been preparation. However, the demonstration that preparation is involved in the reduction of switching costs does not rule out set dissipation as a contributing factor.

An additional aspect of the paradigm is that the four possible interpretations of the target stimulus (UP, DOWN, RIGHT, and LEFT) were mapped to only two response keys. For example, pressing the upper left key either indicated UP or LEFT depending on the task, while pressing the lower right key either indicated DOWN or RIGHT, depending on the task. This set-up was chosen to ensure that the instructional cue will be uninformative with respect to which hand or finger to use to prevent motor preparation (e.g., Miller, 1982; Rosenbaum, 1980). Hence, in half of the trials, the correct key-press was the same for the two tasks (*congruent*), whereas in the other half of the trials, the correct key-press depended on the task (*incongruent* condition). For example, if target location was in the upper left quadrant, the correct responses were UP or LEFT, depending on the task. However, both UP and LEFT were mapped to the upper left response key. Hence, pressing the upper left response key was regarded as correct irrespective of the task. In contrast, pressing the upper left key in response to an upper right target would have been regarded as correct in the context of the UP-DOWN task (where it indicated UP). However, the same was not true in the context of the RIGHT-LEFT task (where the same response indicated LEFT, instead of the correct response, RIGHT).

The cueing paradigm allowed us to distinguish between two manipulable intervals. The first is the period between the response in Trial N-1 and the presentation of the instructional cue in Trial N, or Response–Cue Interval (RCI). Since participants do yet know which task is next, the RCI may be considered as a passive waiting period. The second period separates the presentation of the instructional cue and the target stimulus in Trial N. This period is likely to involve preparatory reconfiguration since the participants already know which task is next. The obvious advantage of this distinction is that it maps nicely to the two processes that were suggested as responsible for the reduction in switching costs. The RCI maps to set dissipation time (i.e., Allport et al.'s, 1994, explanation) while the CTI maps to preparatory reconfiguration time (de Jong, in press; Goschke, in press; Meiran, 1996, in press-a, in press-b; and Rogers & Monsell, 1995).

We have mentioned two contrasting explanations regarding the reduction in switching cost by increasing preparation time. One reason why researchers have not been able to assess the role of each process was the experimental paradigm being used. This paradigm was based on a fixed ordering of tasks and did not make use of instructional cues. Accordingly, researchers have been able to manipulate the Response–Target Interval. In the best case, the Response–Target Interval, as manipulated with fixed task order and without instructional cues, may be considered to be an unanalyzable combination of RCI (related to set dissipation) and CTI (related to set reconfiguration). Unfortunately, even this assumption cannot be guaranteed. The reason is that the participants may have begun preparing for the switch at an unknown point in time prior to responding. For example, if the fixed order of the two tasks, A and B, is AABB . . . participants need not wait until the last Task A response in order to prepare for Task B which follows. Instead, they can prepare sooner, perhaps while executing the previous Task A trial. In short, there is no experimental control over the point in time where task preparation begins.

To reiterate, our purpose was to show that the contrasting explanations given to the reduction in task switching cost are both partly correct and related to different aspects of the cost. The structure of the article is as follows. In Experiments 1 and 2 we manipulated RCI, and the results support Allport et al.'s (1994) notion of passive dissipation. In Experiments 3 and 4 we examined the relation between preparatory reconfiguration and two general preparatory processes. The results show that preparatory reconfiguration is not a by-product of general preparation. In other words, we established the status of reconfiguration as a separate preparatory process.

GENERAL METHOD AND ANALYTIC PROCEDURE

Apparatus and Stimuli

All testing was performed using IBM-PC clones with a 14-inch monitor which were controlled by software written in MEL (Schneider, 1988). Stimuli were drawn in white on a black background using the graphic symbols in the extended ASCII code. They included a 2 × 2 grid that was presented in the middle of screen and subtended approximately 3.4° (width) × 2.9° (height). The target was the smiling-face character (ASCII code 1), which subtended approximately .3° (width) × .5° (height). The arrowheads (ASCII codes 16, 17, 30, and 31) subtended approximately .3° × .3° and were positioned .7° from the end of the grid.

Procedure

Participants were tested individually and received written instructions followed by a short warm-up session (20 trials) and by the experiment itself. A short break was introduced at the end of each experimental block and participants were encouraged to stretch a little. Errors were signaled by a 400-Hz beep for 50 ms. Each response in the warm-up phase was followed by a message that appeared in the center of the screen, which indicated the correct response, the Hebrew words למגלה (UP), למטה (DOWN), \ימי (RIGHT), or שמאל (LEFT).

Participants

All the participants were undergraduate students from Ben-Gurion University of the Negev and the affiliated Sapir College, who participated for partial course credit. Half of the participants in each experiment were assigned to respond with the upper left key (''7,'' indicating UP or LEFT, depending on the task) and the lower right key (''3,'' indicating DOWN or RIGHT). The other half of the participants used the lower left key (''1,'' indicating DOWN or LEFT, depending on the task) and the upper right key (''9,'' indicating UP or RIGHT).

Analytic Method

The first trial in a block, trials which were preceded by errors, or trials in which the RT on the previous trial was longer than 3000 ms were excluded from all analyses. Trials in which RT was longer than 3000 ms were only analyzed for accuracy but not for RT. Because of the random selection of trial parameters (e.g., task, CTI, and target position), the number of observations was not identical across conditions. Therefore, the data of each experimental cell were first averaged and the cell means were entered into an analysis of variance (ANOVA). In addition to RTs and error rates, the mean number of valid observations per condition is reported.

EXPERIMENT 1

In the present experiment, the tasks were ordered randomly. Therefore, participants had to wait for the presentation of the instructional cue in order to know which task to execute. For that reason, they were unlikely to reconfigure during the period when they waited for the instructional cue, i.e., the RCI. Allport et al. (1994) suggested that although participants maintain the task set adopted in the previous trial, as reflected in task-switching cost, this set dissipates partly during the first 1–2 s after responding in Trial N-1. Hence, the prediction was that task-switching cost would be reduced by increasing the RCI. A schematic description of the timing of the displays is presented in Fig. 2.

It is conceivable that participants prepare during the RCI, although the strategy may be irrational. If so, effects of RCI on switching cost would not indicate passive dissipation of the previous task set but would indicate preparation instead. In order to assess whether active preparation took place we employed two criteria regarding the active/passive nature of the underlying process. The first criterion is based on a reversal of reasoning by Rogers and Monsell (1995). Specifically, Rogers and Monsell found that whether task-switching cost was reduced by preparation depended on the blocking

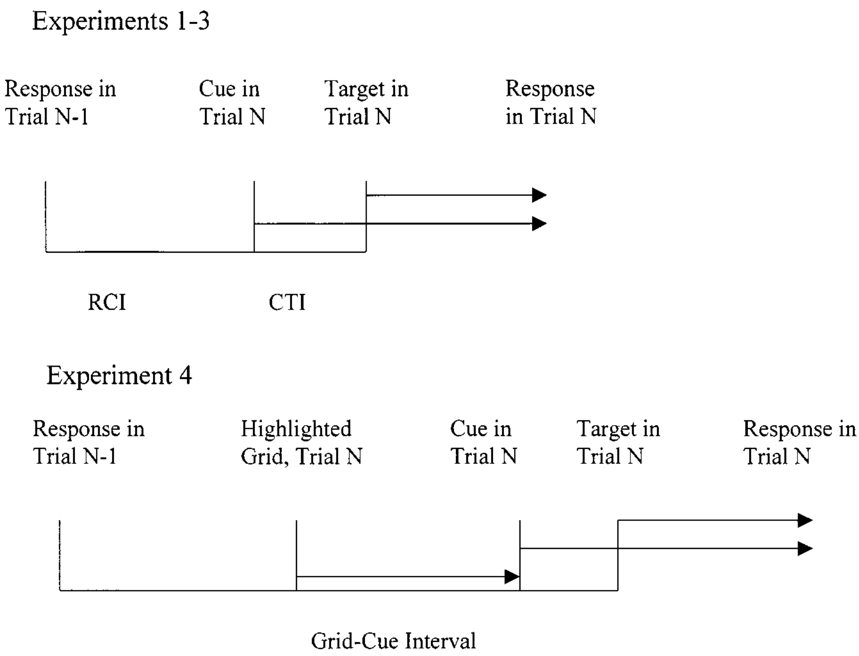

FIG. 2. The timing of the displays.

of the preparatory interval. A reduction in switching cost was found when the preparatory interval was blocked, that is, was constant for a block of trials, but not when the interval varied randomly between trials. The dependence of preparation on the blocking of the preparatory interval was taken as evidence that a strategic process was involved. In the present context, if RCI blocking will result in a faster rate of cost reduction as compared to random RCI, this will suggest that a strategic process was involved. However, if the rate of cost reduction proves insensitive to RCI blocking, this may be taken as evidence that an active strategic process was not involved. The aforementioned comparison was between Group 1 in which RCI was blocked and Group 2 in which RCI varied randomly.

The second criterion was based on expectancy of a task switch. Instead of having an equal probability for a task switch and for a task repetition (50:50) as in Groups 1 and 2, in Group 3, the probability for a task repetition was twice ($p = .67$) the probability for a task switch ($p = .33$). The rationale was that, if the reduction in task-switching cost were mediated by strategic preparation for a task switch, increasing the likelihood of task repetitions would discourage the use of such a strategy. Specifically, the participants would be motivated to keep active the task set they adopted in Trial N-1, since the same set was likely to be used in Trial N. If, however, the rate of cost reduction by RCI proves insensitive to the probability of task repetition, this would suggest that keeping the set active is nonstrategic. Most importantly, if switching cost would be reduced even when participants are motivated to maintain the task set active, this would suggest that cost reduction by increasing the RCI is nonstrategic.

Method

Participants and procedure. Thirty-one participants took part in this experiment. One participant made 12% errors as compared to 5% or less among the other participants. Therefore, the participant was replaced by another participant. Ten participants were assigned to each group, half in each response-key combination, and the assignment was according to order of entry into the experiment. In Group 1, RCI was kept constant throughout the block of trials, and the order of RCIs was randomly determined in each session. In Group 2, RCI varied randomly between trials. In Group 3, RCI was kept constant, as in Group 1, but task repetitions were twice as likely as task switches. The conditions, especially those creating the differences between the groups, were explained to the participants in the beginning of each session.

The experiment consisted of two identical 1-h sessions, each beginning with 20 warm-up trials followed by five experimental blocks, consisting of 96 trials each. Each trial consisted of the following events: (1) the presentation of an empty grid for fixation for an RCI of 132, 232, 432, 1032, or 3032 ms; (2) the presentation of an instructional cue for 117 ms; and (3) the presentation of the target stimulus along with the instructional cue until the response (see Figs. 1 and 2). During the 20 warm-up trials, RCI was 432 ms, the intermediate value.

Design. Group (1, 2, 3) was a between-participants independent variable. RCI (132, 232, 432, 1032, or 3032 ms), Congruency (congruent, incongruent), Task-Switch (switch, no-switch), and Session (1, 2) varied within participants.

Results

The results were clear in showing that task-switching cost was reduced by increasing the RCI. Moreover, the rate of cost reduction was similar in the three groups. These results are consistent with Allport et al.'s (1994) notion regarding passive dissipation of the previous task set (see Fig. 3. and Table 1).

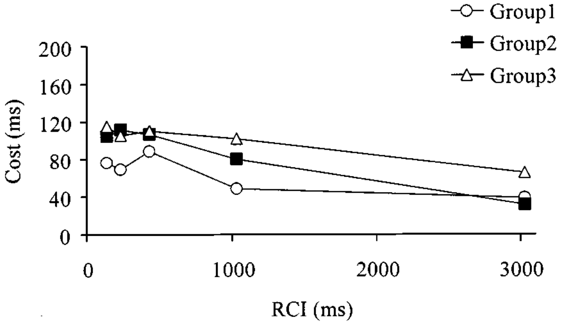

FIG. 3. Task-switching cost (Switch RT − No-Switch RT, in milliseconds) as a function of RCI (ms) and Group in Experiment 1. RCI, Response–Cue Interval. Group 1: Blocked RCI; Group 2: Random RCI; Group 3: Blocked RCI, no-switch more likely than switch.

Response time. The first 10 trials in each block were considered a period during which the participants adjusted themselves to the RCI in that block. Although this consideration does not apply to Group 2, the same procedure was used in all groups to ensure uniform analysis. Another consideration refers to the fact that there was a potential confounding of Group with the number of consecutive task repetitions. This resulted from the fact that the probability for a task repetition was higher in Group 3 than in Groups 1 and 2, since in Group 3 task repetitions were twice as likely as a task switch. Hence, the chances that the same task will repeat many times in a row were higher in Groups 3 than in Groups 1 and 2. In order to correct for this problem, only the first repetition of the task was considered in the main analysis as no-switch, while receptions beyond the second repetition were analyzed separately.

There were, on average, between 11 and 25 valid RTs per condition. The $3 \times 2 \times 2 \times 2 \times 5$ ANOVA indicated three significant main effects, Congruency, $F(1, 27) = 40.49$, $p < .0001$, $MS_e = 31747.24$; Task-Switch, $F(1, 27) = 47.01$, $p < .0001$, $MS_e = 44274.53$; and Session, $F(1, 27) = 80.67$, $p < .0001$, $MS_e = 132834.16$. In addition, there were two significant two-way interactions, one involving Task-Switch and Session, $F(1, 27) = 21.43$, $p < .0001$, $MS_e = 8613.55$, and one involving RCI and Task-Switch, $F(1, 27) = 5.35$, $p < .001$, $MS_e = 6278.48$. Importantly, the interaction between Task-Switch and Group, and the triple interaction between Task-Switch, Group, and RCI were insignificant, $F < 1$. In other words, switching cost and the rate of reduction in the cost were similar in the three groups. The significant two-way interactions reveal that practice (Session) reduced switching cost considerably (from 97 to 53 ms). However, the reduction in switching cost due to practice was statistically the same in the five RCIs. More importantly in the present context, the two-way interaction between RCI and Task-Switch indicates that prolonging the RCI resulted in a systematic reduction in switching cost, as presented in Fig. 3.

As can be seen in Fig. 4, the no-switch RTs increased as the RCI increased. This was confirmed by a separate ANOVA, $F(4, 108) = 3.58$, $p < .01$, $MS_e = 23580.77$. Comparison of adjacent RCIs indicated that the no-switch RTs were faster in the second RCI as compared to the first RCI, $F(1, 27) = 4.58$, $p < .05$, $MS_e = 131408.03$. Moreover, the increase in no-switch RT between the two last RCIs was also significant, $F(1, 27) = 14.77$, $p < .001$, $MS_e = 83494.80$. Finally, the interaction between RCI and Group was insignificant in the analysis of no-switch trials, $F < 1$.

In addition to the significant effects listed above, there was a significant four-way interaction between Session, Task-Switch, Congruency and Group, presented in Fig. 5. We explored the four-way interaction by analyzing the simple triple interaction between Congruency, RCI, and Task-Switch in each group (using the pooled error term). The simple triple interaction was significant in Group 3 only, $F(1, 27) = 8.76$, $p < .01$, $MS_e = 2845.69$ (pooled).

TABLE 1
Mean RT (in Milliseconds) and Proportion of Errors (PE)—Experiment 1[a]

RCI (ms)	Congruency		Session 1 Switch	Session 1 No-switch	Session 1 Cost	Session 2 Switch	Session 2 No-switch	Session 2 Cost
Group 1: Blocked RCI, 50:50								
132	Incong.	RT	937	810	127	739	688	51
		PE	.065	.023	.042	.022	.008	.014
	Cong.	RT	850	756	94	662	628	34
		PE	.003	.000	.003	.000	.000	.000
232	Incong.	RT	877	774	103	747	711	36
		PE	.047	.033	.014	.042	.022	.02
	Cong.	RT	822	700	122	588	572	16
		PE	.004	.000	.004	.000	.000	.000
432	Incong.	RT	907	834	73	724	643	81
		PE	.032	.03	.002	.044	.039	.005
	Cong.	RT	835	721	114	658	576	82
		PE	.015	.007	.008	.000	.000	.000
1032	Incong.	RT	929	876	53	685	618	67
		PE	.036	.007	.029	.012	.012	.000
	Cong.	RT	798	746	52	619	598	21
		PE	.004	.007	−.003	.004	.000	.004
3032	Incong.	RT	932	922	10	684	675	9
		PE	.032	.022	.010	.013	.013	.000
	Cong.	RT	849	755	94	649	608	41
		PE	.004	.000	.004	.000	.000	.000
Group 2: Random RCI, 50:50								
132	Incong.	RT	959	826	133	690	662	28
		PE	.013	.000	.013	.007	.000	.007
	Cong.	RT	922	746	176	694	614	80
		PE	.000	.005	−.005	.004	.000	.004
232	Incong.	RT	975	842	133	703	617	86
		PE	.059	.000	.059	.011	.017	−.006
	Cong.	RT	887	770	117	666	555	111
		PE	.009	.000	.009	.000	.008	−.008

432	Incong.	RT	959	787	172	703	632	71
		PE	.026	.018	.008	.010	.000	.010
	Cong.	RT	860	762	98	681	595	86
		PE	.003	.000	.003	.004	.000	.004
1032	Incong.	RT	967	857	110	713	648	65
		PE	.027	.036	−.009	.019	.000	.019
	Cong.	RT	899	811	88	641	585	56
		PE	.004	.013	−.009	.000	.000	.000
3032	Incong.	RT	952	902	50	705	686	19
		PE	.034	.015	.019	.004	.000	.004
	Cong.	RT	931	907	24	674	644	30
		PE	.007	.000	.007	.000	.000	.000
Group 3: Blocked RCI, 67:33								
132	Incong.	RT	850	754	96	637	545	92
		PE	.056	.037	.019	.038	.010	.028
	Cong.	RT	820	640	180	594	503	91
		PE	.018	.000	.018	.000	.009	−.009
232	Incong.	RT	743	643	100	628	503	125
		PE	.035	.025	.010	.035	.026	.009
	Cong.	RT	709	580	129	547	480	67
		PE	.010	.000	.010	.006	.016	−.010
432	Incong.	RT	907	753	154	589	536	53
		PE	.042	.025	.017	.036	.043	−.007
	Cong.	RT	834	652	182	541	491	50
		PE	.013	.009	.004	.011	.031	−.020
1032	Incong.	RT	806	646	160	613	555	58
		PE	.050	.031	.019	.065	.020	.045
	Cong.	RT	704	573	131	539	478	61
		PE	.011	.017	−.006	.008	.000	.008
3032	Incong.	RT	773	738	35	654	585	69
		PE	.027	.036	−.009	.024	.011	.013
	Cong.	RT	759	626	133	572	552	20
		PE	.000	.000	.000	.006	.000	.006

[a]RCI, Response–Cue Interval; Cong., congruent; Incong., incongruent. The proportions are for no-switch and switch, respectively.

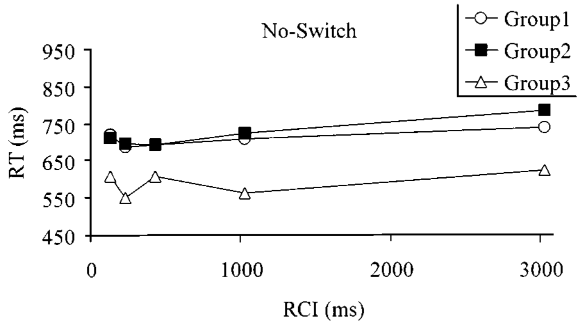

FIG. 4. No-switch RT (in milliseconds) as a function of Group and RCI (ms) in Experiment 1. RCI, Response–Cue Interval.

This interaction reflects the fact that in Session 1, switching cost was larger for congruent than for incongruent trials, $F(1, 27) = 5.47$, $p < .05$, MS_e = 3988.74 (pooled). In contrast, the reverse pattern was nearly significant in Session 2, $F(1, 27) = 4.09$, $p = .053$, MS_e = 1396.71 (pooled). Apparently, the uneven ratio of switch and no-switch trials produced an irregular pattern where switching costs were larger for congruent trials than for incongruent trials, just the opposite to what is usually found.

Errors. Three main effects reached significance including Congruency, $F(1, 27) = 23.15$, $p < .0001$, $MS_e = .0056$; Task-Switch, $F(1, 27) = 8.04$, $p < .01$, $MS_e = .0019$; and Session, $F(1, 27) = 9.91$, $p < .05$, $MS_e = .0011$. In addition, there were two significant interactions, one between Task-Switch and Session, $F(1, 27) = 6.60$, $p < .01$, $MS_e = .0010$, and the other between Task-Switch and Congruency, $F(1, 27) = 5.95$, $p < .05$, $MS_e = .0020$. Task-switching cost in error proportion was reduced from Session 1 to Session 2

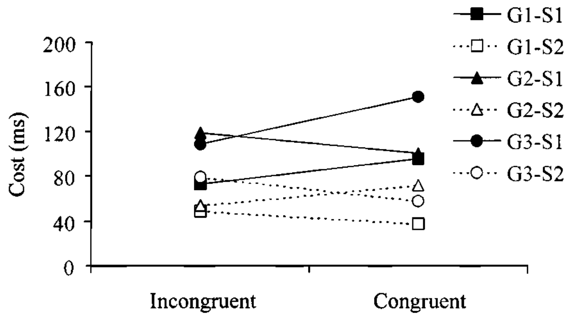

FIG. 5. Task-switching cost (Switch RT − No-Switch RT, in milliseconds) as a function of Congruency, Session, and Group in Experiment 1. G, Group; S, Session; Group 1: Blocked RCI; Group 2: Random RCI; Group 3: Blocked RCI, no-switch more likely than switch.

from 1% (2.3% vs 1.3%) to .5% (1.4% vs .9%). In the congruent condition, there were barely any errors (.5%) and for that reason, no evidence of switching cost. In the incongruent condition, however, there was switching cost (3.2% vs 1.9%).

Effects of Task Repetitions

As a result of increasing the probability for a task repetition over the probability for a task switch in Group 3, a given task accidentally repeated in up to 16 consecutive trials. This enabled us to assess the consequences of such repetitions, an issue previously examined by Rogers and Monsell (1995, Experiment 6). In their experiment, tasks were ordered in runs of four trials, i.e., Task A was repeated four times, followed by four trials of Task B, followed again by four trials of Task A and so forth. Rogers and Monsell found that performance was worse immediately after switching tasks than after repeating tasks, indicating a task-switching cost. However, there was no additional benefit attributed to performing the task several times in a row as compared to repeating it once. This result enabled Rogers and Monsell to rule out several explanations of task-switching cost. Most important in the present context is the micro-practice model. According to the micro-practice model, task-switching cost reflects, at least in part, the operation of a dynamic tracking process which optimizes performance after every response. The model suggests that the system becomes better and better tuned for one task, but less and less tuned for the alternative task, as reflected in a task-switching cost. The micro-practice model predicts that consecutive task repetitions will result in a gradual improvement in performance. This prediction contrasts with the null effect of task repetitions that was observed.

One shortcoming of Rogers and Monsell's experiment is that because task order was constant, the participants could have begun preparing for the task switch while still performing the preswitch trials. Such a strategy is likely to interfere with performance in the preswitch trials and more so toward the end of the run of trials, when a task switch is imminent. Consequently, preparation, causing response retardation, has masked the beneficial effect of task repetition, with the two effects canceling one another and yielding a null effect. Since this scenario is plausible, a more appropriate procedure is to look for the effect task repetition when task switches are unexpected. Under these conditions, participants are unlikely to prepare for the task switch while performing the preswitch trials, and the effect of micro-practice can be observed. These conditions were met in the present experiment.

Our results indicate that task repetitions beyond the 10th were very rare, resulting in many cells with one or zero observations. Therefore, we analyzed only the 1st to 10th task repetitions, all which are considered as no-switch trials, where the average number of valid RTs declined from 236 to 5. There was a significant main effect for Task-Repetition on RT, $F(9, 81) = 7.09$,

FIG. 6. RT (in milliseconds) as a function of Task-Repetition Number, Group 3, Experiment 1.

$p < .0001$, MS_e =1158.85. Only the linear component of the effect was significant, $F(1, 9) = 32.49$, $p < .0005$, $MS_e = 2021.99$, while the remaining orthogonal polynomials were insignificant (Fig. 6).

The present findings are incongruent with Rogers and Monsell's (1995) results in that they show a slight gradual improvement in performance because of task repetitions. However, these results are congruent with a variety of micro-practice models, found in the literature. Strayer and Kramer (1994), for example, have shown evidence for a postresponse fine-tuning process that adopts the appropriate speed–accuracy trade-off. Moreover, Meiran (in press-a) has suggested that a component of task-switching cost is caused by micro-practice. There is an interesting relevant finding by Salthouse, Fristoe, McGurthy, and Hambrick (1998). These authors used a paradigm similar to that used by Rogers and Monsell, except with a zero preparatory interval, and found a small but significant improvement in performance due to task repetition.

Discussion

The present experiment examined Allport et al.'s (1994) notion regarding passive partial dissipation of the task set from the previous trial. We manipulated the RCI in a case in which the participants depended on the instructional cue in order to know what to do next. This was done while keeping the length of the CTI short and constant, thereby limiting preparatory reconfiguration. The results supported the set-dissipation notion by showing that task-switching cost decreased as RCI increased. Moreover, RT in no-switch trials increased, as would be expected if the task set from the previous trial dissipated. The underlying process is most likely to be passive and non strategic, based on two criteria. First, the rate of reduction in task-switching cost was insensitive to RCI blocking (the comparison between Group 1 and Group 2). Second, the rate of reduction in switching cost was not significantly affected by motivating the participants to keep the previous task set active. Motivation was achieved by task repetitions being twice as likely as task switches (the comparison between Groups 1 and 2 on the one hand and Group 3 on the other hand). Note, however, that the present results do not indicate that participants cannot prepare a task during the RCI. The results merely indicate that active preparation was not involved when the two tasks were unpredictable and equally probable.

EXPERIMENT 2

When the RCI was very long in Experiment 1, very little cost remained, especially in comparison to experiments where CTI was manipulated (e.g., Meiran, 1996, in press-b). One reason may be that when CTI is short and constant, as it was in Experiment 1, participants quickly find out that they do not have sufficient time to prepare themselves fully. We suppose that the degree to which one prepares for a given task is at the expense of the readiness to perform a competing task. Consequently, when a short CTI prevents full preparation for a given task, the cost in switching to the competing task is smaller. The major purpose of Experiment 2 was to study the effect of RCI on switching cost under conditions in which CTI varies randomly and task preparation is nearly complete. Our main prediction was that increasing the RCI would reduce switching cost, and at a similar rate as in Experiment 1, except that switching cost would be considerably larger than in Experiment 1, especially given a short CTI. Another goal was to study preparatory reconfiguration and passive set dissipation within the same experiment.

Method

Participants and Procedure

Thirty participants took part in three identical 1-h sessions, and the procedure was similar to that in Group 1 in Experiment 1 (blocked RCI and equal probabilities of task switch and task repetition). There were only two differences between the experiments. First, there were four RCIs (132, 332, 532, and 2032 ms) in Experiment 2 instead of five in Experiment 1. Second, the CTI varied randomly from trial to trial (116, 316, 516, and 2016 ms).

Design

The independent variables in the main analysis were all within participant and included Task-Switch, Congruency, RCI, and CTI.

Results

Response Time

Trial exclusion criteria were the same as in Experiment 1, and the mean number of valid observations per condition ranged between 18 and 22. The $2 \times 2 \times 4 \times 4$ ANOVA revealed significant main effects for Task-Switch, $F(1, 29) = 61.83$, $p < .0001$, $MS_e = 45106.00$; Congruency, $F(1, 29) = 63.68$, $p < .0001$, $MS_e = 55266.64$; and CTI, $F(3, 87) = 33.45$, $p < .0001$,

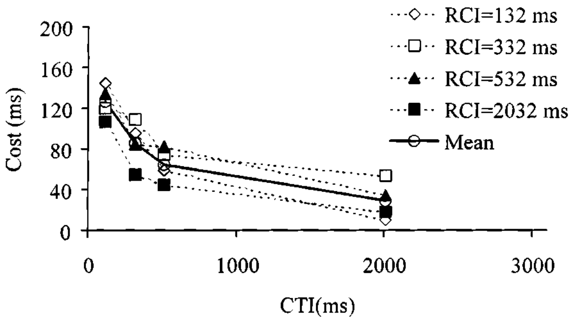

FIG. 7. Task-switching cost (Switch RT − No-Switch RT, in milliseconds) as a function of RCI and CTI (both in milliseconds) in Experiment 2. RCI, Response–Cue Interval; CTI, Cue–Target Interval.

MS_e = 19377.86. In addition, there were significant two-way interactions between CTI and Task-Switch, $F(3, 87) = 35.96$, $p < .0001$, $MS_e = 5533.41$; RCI and Task-Switch, $F(3, 87) = 5.47$, $p < .005$, $MS_e = 4692.31$, Congruency and Task-Switch, $F(1, 29) = 23.59$, $p < .0001$, $MS_e = 3993.52$; and Congruency and RCI, $F(3, 87) = 2.93$, $p < .05$, $MS_e = 3809.14$. Interestingly, the triple interaction between RCI, CTI, and Task-Switch was insignificant, $F = 1.55$, $p = .13$. Finally, switching cost was significant in the longest CTI, $F(1, 29) = 24.22$, $p < .0001$, $MS_e = 4069.80$.

As before, switching cost was larger in the incongruent condition (790 vs 700 ms) than in the congruent condition (691 vs 629 ms). The interaction between RCI and Congruency reflected the fact that in the incongruent condition, RT was 742, 753, 742, and 744 ms in the four RCIs, respectively. In contrast, RT declined systematically as RCI increased in the congruent condition (667, 660, 661, and 649 ms in the four RCIs, respectively). The more interesting interactions are between CTI or RCI and Task-Switch. The interaction between RCI and Task-Switch reflects the fact that mean task-switching cost was 77, 89, 84, and 56 ms in the four RCIs, respectively. The interaction between Task-Switch and CTI is presented in Fig. 7 (also see Table 2).

There are several things to note regarding these interactions. First, an increase in CTI, mainly up to roughly 500 ms, results in a sharp reduction in switching cost, regardless of the RCI. Second, an increase in the RCI beyond 332 ms results in switching cost becoming gradually smaller, as found in Experiment 1. An interesting comparison is between CTI=116 ms and the results of Experiment 1, Group 1, where the CTI was also 116 ms and task switching or task repetition were equally probable. This comparison indicates larger task-switching costs in Experiment 2 than in Experiment 1. While in Experiment 1 switching costs were 71, 66, 72, 47, and 44 ms for the five RCIs, respectively, in Experiment 2 they were nearly twice as large, 144, 120, 134, and 107 ms in the four RCIs, respectively. Averaged across all four CTIs, switching costs in the four RCIs were 77, 89, 84, and 56 ms. These results strongly suggest that when CTI is constant and short (Experiment 1), switching costs become smaller than when CTI is variable and occasionally long (Experiment 2). Moreover, the function relating CTI to switching costs was such that preparation was fastest and most effective until CTI reached approximately .5 s. A similar result was obtained in Experiment 3 and in Meiran's (in press-b) experiments. Hence, if the constant CTI is much shorter than .5 s, this might discourage preparation thereby leading to smaller switching costs as explained in the introduction to the present experiment. Although it is difficult to compare the two experiments due to their differences, the pattern of mean RTs agrees with the conjecture that a constant and short CTI discourages preparation and leads participants to respond while not being fully prepared. On the one hand, the mean RT in Session 1 was virtually identical in the two experiments (832 vs 831 ms). However, in that session, switch RTs were faster in Experiment 1 than in Experiment 2 (873 vs 897 ms), while no-switch RTs were slower in Experiment 1 than in Experiment 2 (789 vs 765 ms).

Errors

There was a triple interaction between CTI, Task-Switch, and Congruency, $F(3, 87) = 4.43$, $p < .01$, $MS_e = .0019$. The variables involved in that interaction were all associated with significant main effects and all two-way interactions were significant. As usual, there were barely any errors in the congruent condition. Therefore, the triple interaction was explored by analyzing the incongruent condition only. There was a significant simple interaction between Task-Switch and CTI, $F(3, 87) = 6.89$, $p < .0005$, $MS_e = .0037$. It reflected the fact that errors were barely influenced by CTI in the no-switch condition (.039, .035, .038, .035, in the four CTIs, respectively). In contrast, the error rate declined steadily in the switch condition, as found for RT (.105, .104, .078, and .061, in the four CTIs, respectively).

Fine-Grained Analyses

In all the following RT analyses, RCI, CTI, and Task-Switch were the independent variables and there was a fourth independent variable, which was different in each analysis.

Task. There were between 19 and 22 valid RTs per condition, on average. Only two sources of variation involving Task reached significance. These were the main effect of Task, $F(1, 29) = 6.84$, $p < .05$, $MS_e = 39790.42$, and the interaction between Task and CTI, $F(3, 87) = 5.26$, $p < .005$, $MS_e = 3323.30$. When the task was UP-DOWN, mean RT was 773, 699, 682, and 693 ms in the four CTIs, respectively. When the task was RIGHT-LEFT, mean RTs were 738, 666, 670, and 678 ms. Importantly, Task did not significantly modulate the effects of CTI and RCI on switching cost.

TABLE 2
Mean RT (in Milliseconds) and Proportion of Errors (PE)—Experiment 2[a]

RCI (ms)	Congruency		CTI = 116 ms Switch	CTI = 116 ms No-switch	CTI = 116 ms Cost	CTI = 316 ms Switch	CTI = 316 ms No-switch	CTI = 316 ms Cost
132	Incong.	RT	866	719	147	784	670	114
		PE	.104	.035	.069	.100	.035	.065
	Cong.	RT	805	665	140	700	622	78
		PE	.008	.009	−.001	.014	.000	.014
332	Incong.	RT	866	740	126	822	670	152
		PE	.111	.050	.061	.110	.045	.065
	Cong.	RT	765	653	112	678	613	65
		PE	.017	.000	.017	.008	.006	.002
532	Incong.	RT	868	716	152	763	665	98
		PE	.103	.034	.069	.102	.027	.075
	Cong.	RT	775	657	118	664	595	69
		PE	.014	.005	.009	.014	.002	.012
2032	Incong.	RT	860	739	121	774	701	73
		PE	.100	.037	.063	.104	.034	.070
	Cong.	RT	757	664	93	645	611	34
		PE	.007	.003	.004	.003	.003	.000

			CTI = 516 ms			CTI = 2016 ms		
			Switch	No-switch	Cost	Switch	No-switch	Cost
132	Incong.	RT	866	719	147	784	670	114
		PE	.104	.035	.069	.100	.035	.065
	Cong.	RT	805	665	140	700	622	78
		PE	.008	.009	−.001	.014	.000	.014
332	Incong.	RT	866	740	126	822	670	152
		PE	.111	.050	.061	.110	.045	.065
	Cong.	RT	765	653	112	678	613	65
		PE	.017	.000	.017	.008	.006	.002
532	Incong.	RT	868	716	152	763	665	98
		PE	.103	.034	.069	.102	.027	.075
	Cong.	RT	775	657	118	664	595	69
		PE	.014	.005	.009	.014	.002	.012
2032	Incong.	RT	860	739	121	774	701	73
		PE	.100	.037	.063	.104	.034	.070
	Cong.	RT	757	664	93	645	611	34
		PE	.007	.003	.004	.003	.003	.000

[a]RCI, Response–Cue Interval; CTI, Cue–Target Interval; Cong., congruent; Incong., incongruent.

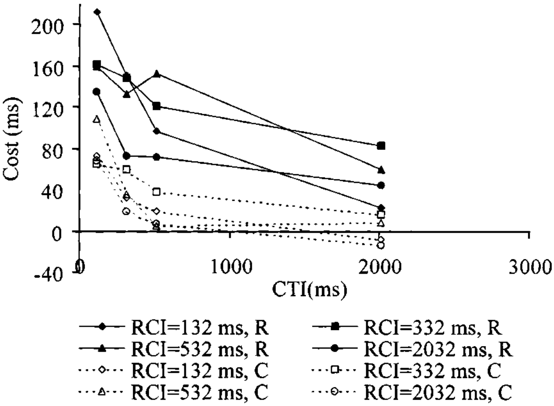

FIG. 8. Task-switching cost (Switch RT − No-Switch RT, in milliseconds) as a function of RCI (in milliseconds), CTI (in milliseconds), and Response-Repetition in Experiment 2. RCI, Response–Cue Interval; CTI, Cue–Target Interval; R, Response repeated; C, Response changed.

Response repetition. There were between 18 and 23 valid RTs per condition, on average. Response-Repetition entered a significant two-way interaction with Task-Switch, $F(1, 29) = 32.70$, $p < .0001$, $MS_e = 23944.83$, but the four-way interaction between RCI, CTI, Response-Repetition, and Task-Switch was also significant, $F(9, 261) = 2.24$, $p < .05$, $MS_e = 3450.14$. The two-way interaction indicated facilitation following response repetition in the no-switch condition (685 and 642 ms when the response alternated or repeated, respectively). However, response repetition slowed responses in the switch condition (718 and 757 ms). Viewed differently, task-switching cost was larger when the response was the same as in the previous trial. As can be seen in Fig. 8, this ordering of RTs was not modulated by the four-way interaction.

Practice. In this analysis, there were between 12 and 15 valid RTs per condition on average. For brevity, we concentrate on how practice (Session) affected switching cost and how it modulated the effects of RCI and CTI on switching costs. Practice drastically reduced switching costs, $F(2, 58) = 50.48$, $p < .0001$, $MS_e = 10810.56$. Interestingly, there was a significant triple interaction between Session, CTI, and Task-Switch, $F(6, 174) = 7.03$, $p < .0001$, $MS_e = 5827.96$, but the parallel triple interaction with RCI was not significant, $F < 1$, thus replicating the results of Experiment 1. The two interactions, one significant one insignificant, are presented in Figs. 9 and 10.

In order to explore the interaction between Session, Task-Switch, and CTI we compared Session 1 to Session 2 in one analysis and Session 2 to Session 3 in a second analysis. The first comparison indicated a significant triple interaction, $F(3, 87) = 8.96$, $p < .0001$, $MS_e = 7578.57$. The same interac-

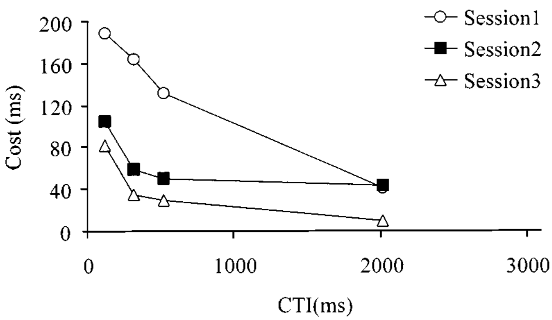

FIG. 9. Task-switching cost (Switch RT − No-Switch RT, in milliseconds) as a function of CTI (in milliseconds) and Session in Experiment 2. CTI, Cue–Target Interval.

tion was insignificant when Session 2 was compared to Session 3, $F < 1$. Nonetheless, switching cost was reduced from Session 2 to Session 3, as indicated by the significant partial interaction between Session and Task-Switch, $F(1, 29) = 18.32$, $p < .0001$, $MS_e = 4154.68$. The difference between Session 1 and Session 2 parallels exactly the practice effects reported by Meiran (1996, Experiment 4). Specifically, the results of both experiments indicate that one session of practice reduced switching costs in the early CTIs, but had no effect whatsoever on the costs in the longest CTI. Analogous results were recently reported by Kramer, Hahn, and Gopher (1999, Experiment 2).

Determining the Fixed RCI in the Next Experiments

In Experiments 3 and 4, we manipulated the CTI while keeping the RCI fixed. The fixed RCI had to be such that most of the reduction in task-switching cost will be due to preparation, and only a negligible portion of cost reduction will be due to set dissipation. The results of Experiment 1 indicated

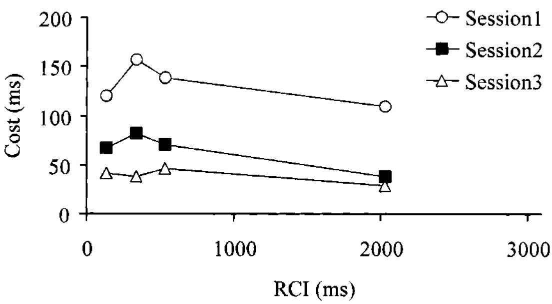

FIG. 10. Task-switching cost (Switch RT − No-Switch RT, in milliseconds) as a function of RCI (in milliseconds) and Session in Experiment 2. RCI, Response–Cue Interval.

a rate of reduction of 4.2 ms cost per 100 ms RCI in the 432–1032 RCI range, and much less, 1.7 ms cost per 100 ms RCI in the 1032–3032 RCI range, which was significant, however, $F(1, 27) = 4.49$, $p < .05$, $MS_e = 109811.53$. In Experiment 2, the average rate was 3 ms cost per 100 ms RCI when RCI increased from 332 to 532 ms and 1.8 ms cost per 100 ms RCI when RCI increased from 532 ms to 2032 ms, $F(1, 29) = 14.02$, $p < .001$, $MS_e = 109150.26$, a value almost identical to that found in the late RCI in Experiment 1.

The results of these two experiments indicate a very slow reduction in switching cost beyond RCI of 532 ms, or 1 s, that is 1.7–1.8 ms cost per 100 ms RCI. Therefore, we decided that the minimal (constant) RCI in the following experiments will exceed 1 s in order to study how preparation reduces switching cost (almost) independently of set dissipation. If the rate of cost reduction were to increase substantially beyond 1.7–1.8 ms cost per 100 ms CTI, this would indicate preparatory reconfiguration.

RECONFIGURATION AND ITS RELATIONSHIP TO GENERAL PREPARATION

One problem in many of the previous demonstrations of reconfiguration, especially Meiran's (1996), is that the reduction in switching cost could have been a by-product of general preparation. In other words, while the experiments may have demonstrated unequivocally that preparation was involved in the reduction in switching cost, they did not necessarily indicate a unique preparatory process, namely reconfiguration.

The critical difference between reconfiguration and general preparation is the domain they apply. While reconfiguration is specific to task switching, general preparation applies equally to switch trials and no-switch trials. The fact that switch RTs were more strongly influenced by preparation as compared to no-switch RTs cannot be taken as unequivocal evidence that reconfiguration is switch-specific. The reason is that the switch condition is more difficult than the no-switch condition. Hence, the switch condition may need more and may benefit more from a highly prepared state. The possibility that reconfiguration is merely a by-product of general preparation must be ruled out in order to permit a less equivocal interpretation of the results concerning preparation-related reductions in switching cost.

Reconfiguration was compared to two forms of general preparation. The first process, predicting target onset, is strategic and has been studied in the context of relatively long preparation intervals (e.g., Niemi & Naatanen, 1981, for review). Its relation to reconfiguration was investigated in Experiment 3. The second process, phasic alertness (Posner & Boies, 1971), is believed to be reflexive, automatic, and fast acting. Phasic alertness has been studied in the context of relatively brief preparatory intervals, typically up to less than 1 s. The relation of reconfiguration and phasic alertness was investigated in Experiment 4.

EXPERIMENT 3

In order to respond efficiently, participants need to accurately predict target onset. This is especially true if the cue and target are remote in time. In the relevant studies, participants performed a single task, and the target stimuli were preceded by a warning signal. In one procedure, foreperiod was manipulated between blocks of trials. In this condition, target onset was predictable and longer foreperiod durations were associated with slower responses. This finding can be explained by less accurate estimations of long durations as compared to short durations, leading to a less accurately predicted target onset with long foreperiods (e.g., Simon & Slaviero, 1975; Niemi & Naatanen, 1981, for review). This effect of foreperiod is not the focus of the current experiment. Of interest are the experiments in which foreperiod varied randomly between trials. The results indicate that increasing the foreperiod led to *faster* responses. One explanation is that participants utilized the probabilistic information conveyed by the passage of time to predict the likelihood of target onset. To demonstrate this point, consider a situation involving three foreperiod durations: short, medium, and long. Just following the warning signal, the probability that the foreperiod will be of a given length is .33, reflecting the equal number of trials in the three foreperiod durations. However, if the elapsed time after the cue has exceeded the short duration, then the foreperiod must be either medium or long, and therefore the probability given the elapsed time has increased to .5. Similarly, if the elapsed time has exceeded the medium duration, then the foreperiod must be long, i.e., the probability has reached 1.00. In summary, the passage of time is informative with respect to foreperiod likelihood (Niemi & Naatanen, 1981, p. 138). This was termed ‘‘aging foreperiod durations.’’ The notions were confirmed in experiments on ‘‘nonaging foreperiod durations’’ where the conditional probability of target onset, given the passage of time, remained constant by manipulating the proportion of trials in the various foreperiod durations, as is explained shortly. The results of these experiments indicate that when foreperiod durations are nonaging, the usual trend for RT reduction with increasing foreperiod duration has been eliminated or even slightly reversed (Baumeister & Jubert, 1969; Naatanen, 1970; Naatanen & Merisalo, 1977; Nickerson & Burnham, 1969).

Possible Interaction Between the Prediction of Target Onset and Preparatory Reconfiguration

Two hypotheses regarding the interaction between reconfiguration and predicting target onset are discussed. The first hypothesis postulates that reconfiguration depends on predicting target onset. For example, Rogers and Monsell (1995) speculated that in order for preparatory reconfiguration to take place two conditions must be met. First, participants must be able to predict target onset. Second, target onset must be sufficiently remote so that the target is not presented while reconfiguration is still in progress, which would result in performance breakdown (Rogers & Monsell, p. 218).

Another form of dependence between predicting target onset and preparatory reconfiguration is competition over the same resources. The competition hypothesis predicts that a high demand of resources by one process will result in less efficiency in the other process. For example, as target onset becomes more probable, more resources may be devoted to maintaining high readiness, taking away resources required for reconfiguration.

The results of Experiment 2 are more in line with the resource competition hypothesis than with the dependence hypothesis. In that experiment, the foreperiod durations were aging. Hence, the likelihood of target onset increased with increasing CTI, meaning that increasing CTI also led to a greater demand of resources by target-onset prediction. Hence, an increase in CTI implied a decrease in the available resources for reconfiguration. Accordingly, the sharpest reduction in task-switching cost was observed during the initial range of CTIs, when more resources were presumably available for reconfiguration. In contrast, the dependence hypothesis may predict that reconfiguration would become possible only toward the end of the CTI, where target onset becomes increasingly predictable.

The present experiment explored further the relation of reconfiguration and the prediction of target onset. The most important manipulation was CTI-Probability, related to target-onset predictability. In the critical group, *mostly short CTIs,* the conditional probabilities of the foreperiod durations (CTIs) were equated. This was achieved by including 50% of the trials in the shortest CTI (132 ms), 50% of the remaining trials in the next shortest CTI, and so forth. In other words, the foreperiod durations were nonaging, with the last CTI being the exception since its conditional probability was 1.00. Two additional groups were tested. In the second group, *equally probable CTIs,* the unconditional probabilities were equal. However, since the CTIs were equally probable, the first two groups differed on two aspects: target onset predictability and even vs uneven distribution of trials among the CTIs. To deal with the latter aspect, we included a third group for whom most CTIs were long. In that group, the distribution of trials among the CTIs was just as uneven as in the first group, except that long CTIs were the most probable and short CTIs were the least probable. Figure 11 presents the conditional probability of target onset as a function of CTI and CTI-Probability. Since the conditional probability is always 1.0 in the last CTI, this value was omitted from Fig. 11.

As can be seen in Fig. 11, when most of the CTIs were short, the conditional probability associated with the first four CTIs was the same, .5. In the

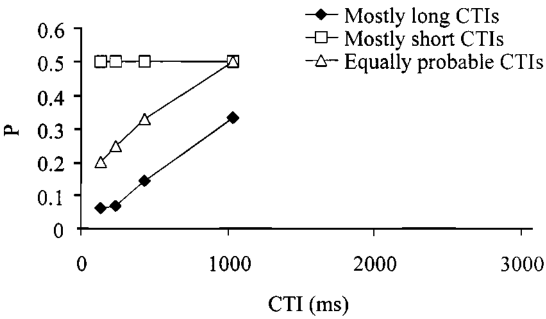

FIG. 11. The probability for a given CTI given the elapsed CTI as a function of CTI (in milliseconds) and CTI-Probability in Experiment 3. CTI, Cue–Target Interval.

remaining two groups, the conditional probability increased with CTI, and hence, an increase in CTI was likely to be associated with an increased expectancy of target onset. In order to minimize the role of set dissipation, the RCI was just over 1 s (see above).

Our predictions refer to two aspects. First, it needs to be demonstrated that participants employ the probabilistic information to predict target onset *in the present paradigm.* This will be reflected in a significant interaction between CTI and CTI-Probability. Specifically, RT was predicted to become shorter by increasing the CTI only when the foreperiod durations are aging, that is, when the CTIs are either mostly long or equally probable. Such a trend was not predicted for the group for whom most CTIs were short, and the foreperiod durations were nonaging (Baumeister & Jubert, 1969; Naatanen, 1970; Naatanen & Merisalo, 1977; Nickerson & Burnham, 1969).

The critical predictions refer to the relation between target-onset prediction and preparatory reconfiguration. We mentioned two hypotheses. The first hypothesis is that reconfiguration depends on target-onset prediction. This hypothesis predicts that cost reduction (indexing reconfiguration) would be found only or mainly given aging foreperiod durations; that is, with equally probable CTIs or mostly long CTIs. In these groups, it is possible to predict target onset, which permits reconfiguration. This was not the case when most of the CTIs were short, since target-onset prediction was impossible. Hence, the first hypothesis predicts that there would be no reconfiguration (that is, cost reduction) when most of the CTIs are short except perhaps in the longest CTI, which was predictable.

The second hypothesis, resource competition, leads to a different prediction. When the foreperiod durations are aging (mostly long CTIs or equally probable CTIs), more resources are available for reconfiguration in the beginning CTI. Hence, the hypothesis predicts that the sharpest cost reduction will be found in the initial CTI. In contrast, a more gradual cost reduction was predicted for nonaging foreperiod durations (mostly short CTIs). In that condition, the probability of target onset was unaffected by CTI, hence equal resources were available for reconfiguration throughout the CTI range.

Method

Participants and Procedure

Ten participants were assigned to each of the three groups ($N = 30$) according to the order of entry. Each participant took part in two identical 1-hr sessions. A session began with 20 warm-up trials and consisted of four experimental blocks, each with 125 trials (for the group for whom CTIs were equally probable) or 128 trials (for the remaining two groups). During warm-up, 75% of the targets were incongruent, which forced participants to pay close attention to the instructional cues. When most CTIs were short, each experimental block included 64 trials with CTI = 132 ms, 32 trials with CTI = 232 ms, 16 trials with CTI = 432 ms, and 8 trials in each of the remaining CTIs. Exactly the reverse assignment was used for the group for whom most of the CTIs were long: 64 trials in the longest CTI, 32 trials in the second longest CTI, and so on. In the group for whom all CTIs were equally probable, there were 25 trials in each CTI. The RCI was 1016 ms.

Design

CTI-Probability was manipulated between participants (mostly short CTIs, mostly long CTIs, and equally probable CTIs). CTI (132, 232, 432, 1032, and 3032 ms), Congruency (congruent vs incongruent), and Task-Switch (no switch vs switch) varied within participant.

Results

Response Time

The mean number of nonmissing RTs per condition ranged between 13 and 129. This large range reflects the manipulation of CTI-Probability. The $3 \times 2 \times 2 \times 5$ ANOVA revealed three significant main effects including Congruency, Task-Switch, and CTI, *F*s (1, 27; 1, 27; and 4, 108) = 52.30, 71.23, and 45.75, $p < .0001$, MS_es = 16059.97, 10499.04, and 6320.64, respectively. In addition, two two-way interactions were significant, CTI by

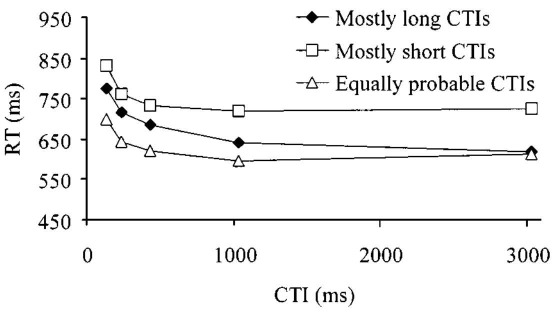

FIG. 12. RT (in milliseconds) as a function of CTI (in milliseconds) and CTI-Probability in Experiment 3. CTI, Cue–Target Interval.

Task-Switch and Congruency by Task-Switch, $Fs(4, 108$ and $1, 27) = 20.73$, 8.19, $p < .0001$, $.01$, $MS_e = 2126.28$, 2994.02, respectively. The predicted interaction between CTI and CTI-Probability only approached significance, $F(8, 108) = 2.55$, $p = .11$, $MS_e = 6320.24$ (Fig. 12).

The marginally significant interaction between CTI and CTI-Probability may be taken as evidence that the participants did not use the probabilistic information to predict target onset. However, we believe such a conclusion to be inaccurate for the following reasons. First, predicting target onset was typically studied using relatively long foreperiod durations of .5 s and above. In the present experiment, we included short CTIs, where there was insufficient time to predict target onset. Putting all the CTIs into the same analysis may have therefore resulted in the dilution of the effect, which eventually fell short of significance. Second, there was evidence that another preparatory process dominated in the initial CTIs. The evidence includes the dramatic reduction in RT and the equal rate of reduction in RT over that range among the three groups. If target-onset prediction were the only reason for the effect of CTI on RT, such an effect would not be predicted for nonaging foreperiods. The fact that CTI led to response speeding over that initial range of CTIs, and equally so in the three groups, suggests that another process dominated in that range of CTIs.

For these reasons, we conducted two separate analyses. In the first analysis we concentrated on the short CTIs (132, 232, and 432 ms). In this analysis, the interaction between CTI and CTI-Probability did not approach significance, $F < 1$. In other words, there was no evidence for the prediction of target onset. In the second analysis, we included CTIs longer than or equal to 432 ms (432, 1032, and 3032 ms). In that analysis, the interaction between CTI and CTI-Probability was significant, $F(4, 54) = 2.62$, $p < .05$, $MS_e = 4878.86$. As predicted, when most of the CTIs were long, CTI affected RT beyond 432 ms, whereas this did not occur when most of the CTIs were short. Separate analyses within each CTI-Probability, using the pooled error term, supported this impression, where the effect of CTI was insignificant when most of the CTIs were short, $F < 1$, or equally probable, $F = 1.50$, but was significant when most of the CTIs were long, $F(2, 54) = 10.09$, $p < .0005$, $MS_e = 4878.86$ (pooled). Hence, there was evidence that the participants employed the probabilistic information to predict target onset.

The significant interaction between CTI and Task-Switch is similar to that found in Experiment 2 and in Meiran's (in press-b) experiments. An increase in CTI led to a reduction in task-switching cost, which was most dramatic over the initial range of CTIs (Fig. 13). A significant task switching cost was observed in the longest CTI, $F(1, 27) = 23.02$, $p < .0001$, $MS_e = 1189.34$, indicating a residual cost. Switching costs at that CTI were not significantly affected by CTI-Probability, as indicated by an insignificant simple interaction between Group and Task-Switch, $F < .1$.

The triple interaction involving CTI, Task-Switch, and CTI-Probability

TABLE 3
Mean RT (in Milliseconds) and Proportion of Errors (PE)—Experiment 3[a]

CTI (ms)	Congruency		Mostly long CTIs Switch	Mostly long CTIs No-switch	Mostly long CTIs Cost	Mostly short CTIs Switch	Mostly short CTIs No-switch	Mostly short CTIs Cost	Equally probably CTIs Switch	Equally probably CTIs No-switch	Equally probably CTIs Cost
132	Incong.	RT	903	730	173	936	824	112	782	668	114
		PE	.074	.012	.062	.042	.020	.022	.046	.014	.032
	Cong.	RT	781	689	92	843	728	115	735	619	116
		PE	.009	.000	.009	.007	.002	.005	.000	.003	−.003
232	Incong.	RT	803	685	118	871	760	111	736	613	123
		PE	.048	.000	.048	.041	.016	.025	.047	.015	.032
	Cong.	RT	740	641	99	750	673	77	653	571	82
		PE	.006	.000	.006	.005	.000	.005	.006	.000	.006
432	Incong.	RT	783	671	112	812	762	50	684	626	58
		PE	.039	.000	.039	.030	.034	−.004	.030	.006	.024
	Cong.	RT	679	616	63	670	688	−18	608	570	38
		PE	.006	.000	.006	.007	.004	.003	.003	.000	.003
1032	Incong.	RT	707	649	58	793	731	62	651	606	45
		PE	.018	.007	.011	.052	.023	.029	.020	.013	.007
	Cong.	RT	634	573	61	686	670	16	592	533	59
		PE	.002	.001	.001	.000	.000	.000	.000	.000	.000
3032	Incong.	RT	672	634	38	806	738	68	637	627	10
		PE	.020	.005	.015	.058	.026	.032	.013	.021	−.008
	Cong.	RT	597	570	27	674	682	−8	617	570	47
		PE	.002	.002	.000	.000	.007	−.007	.000	.000	.000

[a]CTI, Cue–Target Interval; Cong., congruent; Incong., incongruent.

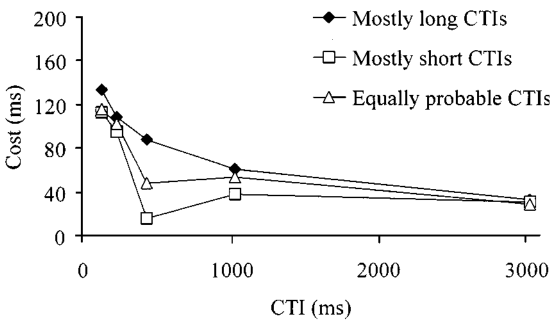

FIG. 13. Task-switching cost (Switch RT − No-Switch RT, in milliseconds) as a function of CTI (in milliseconds) and CTI-Probability in Experiment 3. CTI, Cue–Target Interval.

was insignificant, $F < 1$. A similar analysis which included the three longest CTIs only (where there was evidence for the prediction of target onset) found that the reduction in switching cost, indexed by the interaction between Task-Switch and CTI, was no longer significant, $F = 1.90$, $p = .16$. The triple interaction, which involved CTI-Probability was also insignificant in that analysis. In comparison, when the first three CTIs were analyzed, the interaction between CTI and Task-Switch was significant, $F(2, 54) = 17.69$, $p < .0001$, $MS_e = 2210.59$, while the triple interaction involving CTI-Probability was still insignificant, $F = 1.14$.

It was found that responses were faster in the congruent condition than in the incongruent condition, but this effect was larger in the switch condition (772 vs 688 ms, or an effect of 84 ms) than in the no-switch condition (684 vs 626 ms, or an effect of 42 ms). It should be noted that, as found in Experiment 2, the triple interaction involving Congruency, Task-Switch, and CTI was insignificant, $F < 1$, which suggests that Congruency did not affect the rate of preparatory reconfiguration.

Errors

Analysis of errors revealed a similar picture to that found in the RT analysis. There were two significant main effects, Task-Switch and Congruency, $F(1, 27) = 20.44$ and 35.07, $p < .0001$, $MS_e = .001257$ and $.002446$. In addition, there were two significant interactions including CTI by Task-Switch, $F(4, 104) = 2.62$, $p < .05$, $MS_e = .000575$; and Congruency by Task-Switch, $F(1, 27) = 18.71$, $p < .0005$, $MS_e = .000995$. Increasing the CTI led to a reduction in task-switching cost, which was 2% when CTI was 132 and 232 (reflecting the difference in error rate between 3% and 1% in the switch and no-switch conditions respectively) and only 1% in the longer CTIs (2% vs 1%). The effect of Congruency was larger in the switch condition (3.8% errors in the incongruent condition vs only 0.3% in the congruent condition) than in the no-switch condition (1.4% vs 0.1%).

Fine Grained Analyses

All the following analyses were performed on the results of the group with equally probable CTIs ($N = 10$), where there the number of observations was sufficiently large.

Response repetition. A $2 \times 2 \times 2 \times 5$ ANOVA was performed with the independent variables of Response-Repetition, Task-Switch, Congruency, and CTI, and each condition represented, on average, between 20 and 28 nonmissing RTs. The only significant source of variation associated with Response-Repetition was an interaction with Task-Switch, $F(1, 9) = 27.85$, $p < .0005$, $MS_e = 3833.01$. Like in Experiment 2, there was a larger task-switching cost when the response was repeated (689 vs 587 ms, or 102 ms) than when the response changed (649 vs 612 ms, or 37 ms). Viewed differently, response repetition facilitated RT in the no-switch condition, $F(1, 9) = 8.04$, $p < .05$, $MS_e = 3773.02$, and slowed responses significantly in the switch condition, $F(1, 9) = 14.81$, $p < .005$, $MS_e = 5597.01$.

Task. There were on average 22–27 nonmissing RTs per condition when Task, Congruency, Task-Switch, and CTI were included in the ANOVA. Task had a significant main effect, $F(1, 9) = 6.36$, $p < .05$, $MS_e = 14424.63$, reflecting somewhat faster right–left decisions (620 ms) than up–down decisions (650 ms) as found in Experiment 2. However, Task did not enter any significant interaction, neither did it enter a significant source of variance in error rates. This discrepancy from Meiran's (1996) results, where Task was not associated with any significant sources of variation probably reflects an increased statistical power in the present experiments.

Practice. The $2 \times 2 \times 5$ ANOVA included Session, Task-Switch, and CTI as independent variables, with an average of 44–51 valid RTs per condition. Session was associated with a significant main effect, $F(1, 9) = 29.85$, $p < .0001$, $MS_e = 19268.16$, and entered into a significant interaction with CTI, $F(4, 36) = 5.22$, $p < .005$, $MS_e = 1368.22$, and with Task-Switch, $F(1, 9) = 8.38$, $p < .05$, $MS_e = 2202.35$. Importantly, the triple interaction involving Task-Switch, CTI, and Session was not significant, $F < 1$, unlike in Experiment 2 and in Meiran's (1996) Experiment 4. Practice reduced switching cost from 88 ms (733 vs 645 ms) in Session 1 to 50 ms (607 vs 557 ms) in Session 2. Switching cost in the shortest CTI was reduced from 139 ms in Session 1 to 106 ms in Session 2 (an improvement of 33 ms). However, the improvement in the longest CTI was a little greater numerically. In Session 1 switching cost was 58 ms, while in Session 2 the cost vanished to -2 ms. This trend is in opposite, numerically, to that found in Experiment 1 and in Meiran's (1996) fourth experiment. The significant interaction between Session and CTI reflects the following trend. The gain from CTI was larger in Session 1, a maximum reduction in RT of 131 ms (771, 705, 682, 640, 648 ms in the five CTIs, respectively). These values compare to Session 2, where the maximum reduction in RT was only 84 ms (636, 581, 564, 552, and 577 ms).

Discussion

There was evidence that participants employed the probabilistic information conveyed by the passage of time to predict target onset. However, this was true only when most CTIs were long and was evident only for the relatively long CTIs. In that group, RT continued to decrease until the last CTI. In the other groups, RT was barely affected by CTI when CTI exceeded 432 ms. Hence, the results indicate that predicting target onset is *not* an important factor in the standard condition when CTIs were equally probable. The fact that switching cost was reduced even when predicting target onset was impossible (mostly short CTIs) is the strongest evidence against the dependence hypothesis in the present experiment.

There was also no evidence favoring the resource competition hypothesis. Specifically, the resource competition hypothesis explains why switching cost is most dramatically reduced over the initial range of CTIs by assuming that target onset is not highly predicted in that range. However, there was no evidence for target onset prediction in the initial range of CTIs, as revealed in two observations. First, RT was sharply reduced by CTI in the initial range of CTIs even when predicting target onset was impossible. Second, response speeding rate was unaffected by Group over the initial range of CTIs. Moreover, there was another prediction of the resource competition hypothesis, which was not supported. Specifically, the hypothesis predicted that cost reduction would be more gradual when the foreperiods are nonaging, whereas we found that the rate of switching cost reduction was numerically fastest in that condition. In short, we found no evidence for an interaction between predicting target onset and reconfiguration.

EXPERIMENT 4

The purpose of Experiment 4 was to explore the relation between reconfiguration and phasic alertness. Phasic alertness is related to a momentary elevation in responsiveness. The results by Posner and Boies (1971) and other authors suggest that the effects of phasic alertness on RT reach a maximum within about .5 s after the warning signal. In Experiment 3, an increase in CTI up to 432 ms led to a sharp reduction in RT; this may be taken as evidence for phasic alertness. The fact that there was no interaction between CTI and CTI-Probability in that range supports the interpretation. Moreover, switching costs were reduced most sharply during the same interval. This leaves open the possibility that reconfiguration is a by-product of phasic alertness. In order to establish the status of reconfiguration as a distinct preparatory process we needed to rule out this possibility.

The critical manipulation in the present experiment involved phasic alertness introduced by a sharp change in stimulus size. This was achieved by having participants focus on a small ''+'' sign instead of the empty grid which was used for fixation in the other experiments. The ''+'' sign was replaced by a much larger highlighted grid. The highlighted grid carried no task information. However, it was predicted to elicit phasic alertness. It was followed after a variable Grid–Cue Interval by an instructional cue and then, after a fixed and short CTI, by a target stimulus. Although most of the work on phasic alertness has employed auditory warning stimuli with visual target stimuli, we used a visual warning stimulus—the highlighted grid. There were two reasons for our choice. First, the argument, which we wanted to disprove, holds that instructional cues elicit phasic alertness whose by-product is reconfiguration. Moreover, the instructional cues were visual. Second, using auditory warning stimuli introduces a modality shift, which may be quite similar to task switching in the sense of its being associated with a cost (e.g., Rist & Cohen, 1991). Consequently, auditory warning signals may interfere with performance rather than facilitate it in the context of the task-switching paradigm.

If reconfiguration were a by-product of phasic alertness, then phasic alertness alone would be sufficient to reduce switching cost. However, if reconfiguration is a distinct preparatory process, then alertness alone should affect switch trials and no-switch trials to the same extent. In other words, alertness should not lead to a reduction in switching cost.

Because of the change in the fixation stimulus we manipulated CTI in separate blocks of trials to show that the standard finding concerning a reduction in switching cost by preparatory reconfiguration is replicable despite the procedural change. In these blocks there was a ''+'' sign for fixation, followed by a stimulus composed of the standard grid and an instructional cue, that was presented for a variable CTI, followed by the target stimulus and the cue until the response. Note that the instructional cue in the CTI manipulation involved a sharp increase in stimulus size. Hence, the cue was predicted to elicit phasic alertness, just as in the Grid–Cue Interval manipulation. The difference between these conditions was that the CTI manipulation presumably involved phasic alertness and preparatory reconfiguration, whereas the Grid–Target Interval manipulation involved phasic alertness only. In both conditions, the fixation stimulus was presented for an RCI of 2016 ms to minimize the role of set dissipation.

To summarize, participants were tested in two conditions, a critical condition, which involved a manipulation of phasic alertness (Grid–Cue Interval), and a replication condition involving a CTI manipulation. We predicted that RT would be reduced over the initial Grid–Cue Interval. No effect of the Grid–Cue Interval on the size of task-switching cost was predicted, namely the manipulation was predicted to have a similar effect in the switch condition and the no-switch condition. In contrast, the CTI manipulation was predicted to affect RT in no-switch trials (reflecting mainly phasic alertness) and task-switching cost (reflecting preparatory reconfiguration).

Method

Participants

There were 20 participants in this experiment. Each experimental block was either associated with a CTI manipulation or with a manipulation of the Grid–Cue Interval (GCI). Participants were randomly assigned to two testing orders. For half of them, the four blocks involved the manipulations CTI-GCI-GCI-CTI, while for the remaining participants the order was GCI-CTI-CTI-GCI. Hence, the two manipulations were counterbalanced both within participants (through an ABBA or a BAAB design) and between participants.

Stimuli and Procedure

Two stimuli were added. There was a small ''+'' sign for fixation, which overlapped with the center of the grid and subtended approximately $.3° \times .3°$. In addition, there was a highlighted grid, which had the same size as the standard grid used in all the other experiments, except that double lines were used to depict it instead of a single line. The participants took part in a single 1-h session, which consisted of practice (20 trials) and four experimental blocks of 170 trials each. Since some experimental blocks involved a change in manipulation, the first 10 trials in each block were not analyzed and were considered as an adaptation period.

A trial in the Grid–Cue Interval manipulation consisted of the following events: After the response on the previous trial, (1) a ''+'' sign was presented for 2016 ms; followed by (2) a standard grid for 66 ms; followed by (3) the highlighted grid for 66, 366, 516 or 1016 ms; followed by (4) a stimulus consisting of the standard grid and the instructional cue for 166 ms; after which time (5) the target stimulus was presented inside the grid with the entire stimulus presented until the participant responded. The highlighted grid was preceded by a standard grid to create a blinking effect that would result in alertness. Measured from the presentation of the standard grid, the Grid–Cue Interval was 132, 432, 582, and 1082 ms and the Grid–Target Interval was 298, 598, 748, and 1248 ms.

A trial in the CTI manipulation was similar, except that, after the ''+'' sign, the instructional cue was presented along the standard grid for 166, 532, 682, and 1182 ms. This was followed by the target stimulus, presented inside the grid until the response. Note that the shortest CTI was the same as the constant CTI in the Grid–Cue Interval manipulation to permit a comparison between the manipulations.

Results

There were between 18 and 21 valid RTs per condition on average. Separate analyses were performed on results corresponding to the two manipulations and a joint analysis compared the shortest CTI in the CTI manipulation to the conditions in the Grid–Cue Interval manipulation (Table 4).

Grid–Cue Interval Manipulation: Phasic Alertness

Response time. The results supported our predictions in showing that an increase in the Grid–Cue Interval led to RT facilitation but did not significantly affect task-switching cost (see Fig. 14). These conclusions were con-

TABLE 4
Mean RT (in Milliseconds) and Proportion of Errors (PE)—Experiment 4[a]

GTI (ms)	Congruency		Switch	No-switch	Cost
		Grid–cue interval manipulation			
132	Incong.	RT	829	733	96
		PE	.054	.025	.029
	Cong.	RT	715	635	80
		PE	.003	.005	−.002
432	Incong.	RT	795	711	84
		PE	.035	.016	.019
	Cong.	RT	669	601	68
		PE	.003	.003	.000
582	Incong.	RT	793	720	73
		PE	.035	.020	.015
	Cong.	RT	682	612	70
		PE	.003	.000	.003
1082	Incong.	RT	822	719	103
		PE	.053	.020	.033
	Cong.	RT	667	635	32
		PE	.006	.002	.004
		CTI manipulation			
166	Incong.	RT	878	738	140
		PE	.049	.017	.032
	Cong.	RT	756	629	127
		PE	.005	.002	.003
532	Incong.	RT	747	685	62
		PE	.041	.012	.029
	Cong.	RT	645	587	58
		PE	.000	.000	.000
682	Incong.	RT	742	691	51
		PE	.034	.021	.013
	Cong.	RT	622	589	33
		PE	.003	.002	.001
1182	Incong.	RT	716	674	42
		PE	.023	.019	.004
	Cong.	RT	627	566	61
		PE	.003	.002	.001

[a]CTI, Cue–Target Interval; Cong., congruent; Incong., incongruent.

firmed by a 4 × 2 × 2 ANOVA which included the independent variables Grid–Cue Interval, Task-Switch, and Congruency. There were significant main effects of Grid–Cue Interval, $F(3, 57) = 5.53$, $p < .005$, $MS_e = 3074.90$; Congruency, $F(1, 19) = 43.63$, $p < .0001$, $MS_e = 23460.96$; and Task-Switch, $F(1, 19) = 32.23$, $p < .0001$, $MS_e = 14168.53$. None of the interactions were significant, including the interaction between Grid–Cue Interval and Task-Switch, $F < 1$. The difference between the first two Grid–

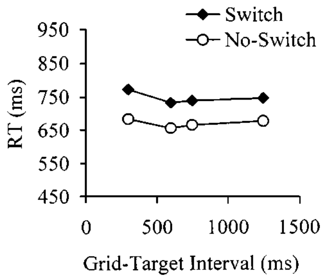

FIG. 14. RT (in milliseconds) as a function of Task-Switch and Grid–Target Interval (in milliseconds) in Experiment 4.

Cue Intervals was significant, $F(1, 19) = 11.86$, $p < .005$, $MS_e = 30956.31$, (772 vs 732 in the switch condition and 683 vs 636 in the no-switch condition) but the other two comparisons of adjacent intervals were insignificant.

Errors. There was a significant main effect of Congruency, $F(1, 19) = 24.99$, $p < .0001$, $MS_e = .0027$; and Task-Switch, $F(1, 19) = 9.86$, $p < .01$, $MS_e = .0027$; and a two-way interaction between these variables, $F(1, 19) = 11.03$, $p < .005$, $MS_e = .0009$. Performance was essentially error-free in the congruent condition (.3 and .2% errors in the switch condition and the no-switch condition, respectively). However, there were some errors in the incongruent condition, mostly after a task switch (4.4%) but also after task repetition (2.0%).

CTI Manipulation: Preparatory Reconfiguration

Response time. The ANOVA was similar to the previous one, except that CTI replaced Grid–Cue Interval. There were significant main effects for CTI, $F(3, 57) = 31.19$, $p < .0001$, $MS_e = 5695.18$; Congruency, $F(1, 19) = 19.19$, $p < .0005$, $MS_e = 47119.66$, and Task-Switch, $F(1, 19) = 18.84$, $p < .0005$, $MS_e = 21743.73$. In addition, there was a significant interaction between Task-Switch and CTI, $F(3, 57) = 7.87$, $p < .0005$, $MS_e = 4433.85$, indicating a replication of previous results, especially Experiments 2 and 3. Importantly, CTI affected RT in the no-switch condition, $F(3, 57) = 7.20$, $p < .0005$, $MS_e = 4088.83$. Comparison of adjacent CTIs indicated that the difference in RT between CTI = 166 to CTI = 532 ms was significant, $F(1, 19) = 6.71$, $p < .05$, $MS_e = 26275.23$ (684 vs 656 ms), but the remaining two comparisons were insignificant.

Errors. The findings indicated two significant main effects, for Congruency, $F(1, 19) = 11.44$, $p < .005$, $MS_e = .0043$; and Task-Switch, $F(1, 19) = 8.54$, $p < .01$, $MS_e = .0010$, as well as a 2-way interaction between the variables, $F(1, 19) = 8.96$, $p < .01$, $MS_e = .0007$. Like before, there were practically no errors in the congruent condition (.1% and .3%) and somewhat more errors in the incongruent condition (3.7% and 1.7% in the switch condition and the no-switch condition, respectively).

Comparison of the Manipulations

The shortest CTI in the CTI manipulation was equivalent to the fixed CTI in the Grid–Cue Interval manipulation. This enabled us to compare the two manipulations. Statistical analysis confirmed the impression that task-switching cost was smaller in the Grid–Cue Interval manipulation than in the CTI manipulation, Fs(1, 19) = 4.72, 5.01, 6.68, 8.05, $p < .05$, MS_es = 35598.91, 52785.61, 45823.99, 43069.25, for the comparison of shortest CTI in the CTI manipulation with the first through fourth Grid-Cue Interval, respectively.

Discussion

The results of Experiment 4 confirm that, in the present paradigm, the effect of phasic alertness reaches a maximum within about .5 s after the presentation of an alerting stimulus (Fig. 14). These findings are in line with previous results (e.g., Posner & Boies, 1971). Numerically, the reduction in RT in the no-switch condition was comparable in the two manipulations, 47 ms in the CTI manipulation and a little less, 28 ms in the Grid–Cue Interval manipulation. However, in spite of the similar alertness-related facilitation, switching cost was significantly reduced only when CTI was manipulated. These results indicate that reconfiguration is not a by-product of phasic alertness and support the interpretation of reconfiguration as being a distinct form of preparation. Rogers and Monsell (1995, Experiment 5) presented a visual alerting stimulus .5 s before they presented the target stimulus. In their design, there were no cues because task order was fixed. Their results also suggest that alerting did not reduce switching costs. Nonetheless, in their experiment, the alerting stimulus was presented after the participants were given a relatively long preparatory interval. That is, they did not explore the role of alertness in the initial reduction in switching costs.

As may be recalled, switching costs in Experiment 1 were considerably smaller than in Experiment 2. The difference in switching costs between the two manipulations in the present experiment was similar in size. This difference could be attributed perhaps to the constant and short CTI, which was

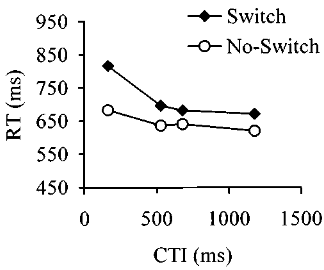

FIG. 15. RT (in milliseconds) as a function of Task-Switch and CTI (in milliseconds) in Experiment 4. CTI, Cue–Target Interval.

used in the Grid–Cue Interval manipulation as opposed to the varying CTI in the CTI manipulation. Specifically, switching costs were 88, 76, 72, and 68 ms in the four Grid–Cue Intervals, respectively, all referring to CTI = 116 ms. These values compare to switching cost of 132 ms with CTI = 116 ms when a highlighted grid did not precede the instructional cue; that is, when CTI was manipulated.

GENERAL DISCUSSION

The present results reconcile two opposing views regarding the reduction in switching costs by prolonging the preparatory interval. According to one view (Rogers & Monsell, 1995; but see also De Jong, in press; Fagot, 1994; Goschke, in press; Meiran, 1996, in press-a, in press-b) the reduction in switching costs reflects preparatory reconfiguration. According to the alternative view (Allport et al., 1994) switching cost reduction reflects passive dissipation of the previous task set. We capitalized on the advantages of the cueing paradigm (e.g., Shaffer, 1965; Sudavan & Taylor, 1987) and our results indicate that both these processes operate in the present task-switching paradigm. Prolonging the RCI resulted in cost reduction, in line with the set dissipation hypothesis. In addition, prolonging the CTI resulted in a further reduction in switching costs, indicating reconfiguration.

The present results also reaffirm previous conclusions concerning preparatory reconfiguration by ruling out alternative explanations. Most importantly, it was shown that reconfiguration is not a by-product of general preparation, including phasic alertness and predicting target onset. We have shown that reconfiguration was as efficient when target onset prediction was possible as it was when target onset prediction was impossible. Furthermore, it was shown that presenting a large highlighted stimulus in the beginning of a trial produced phasic alertness, as did the instructional cue. However, unlike the instructional cue, the alerting stimulus did not reduce switching costs. Hence, phasic alertness was not sufficient for reconfiguration to take place. Either task-information or its combination with phasic alertness was required to elicit reconfiguration.

Following Fagot (1994) (see also Goschke, in press; Meiran, 1996, in press-a, in press-b; Rogers & Monsell, 1995) we suggest that task-switching cost has several components, reflecting various underlying processes. Fagot studied, in addition to the switch condition and the no-switch condition, a ‘‘pure list’’ condition, where the participants performed the same task in succession. He suggested that at the molar level there is the *task-alternation cost*, reflecting the difference between the switch condition and the pure-list condition. The task-alternation condition can then be decomposed into two components: the difference between the pure-list condition and the no-switch condition, which is the *mixed-list cost*. The other component is the difference between the switch condition and the no-switch condition, *switching cost* (see Kray & Lindenbereger, 2000; Los, 1999-a, 1999-b; for similar distinctions).

The present work concentrated on switching cost. This component consisted of two subcomponents in Fagot's (1994) formulation, a *preparatory component* and a *residual component* (to avoid confusion, we use our terms, although Fagot's terms were different). The preparatory component reflects the reduction in switching cost by preparation, while the residual component reflects switching cost given plenty of time to prepare. In the present work, we found significant switching costs given CTI of over 3 s, suggesting that further preparation was unlikely to eliminate it. Nonetheless, the interpretation of the residual costs is controversial. Some authors suggest that it reflects intrinsic limitation (especially Allport et al., 1994; Rogers & Monsell, 1995), while de Jong (in press) suggests it reflects lack of motivation to prepare. The present results suggest that, even if residual costs reflect an intrinsic limitation, this limitation is transient and can be overcome by practice (e.g., Experiment 2).

One contribution of the present work is the suggestion that switching cost has a third component, the ''*dissipating component.*'' This component reflects the reduction in switching cost by prolonging the RCI. Goschke (in press) has recently reported a study where there was a reduction in switching costs by prolonging the RCI. However, there were several shortcomings in his experiment with respect to set dissipation. (We acknowledge the fact that set dissipation was not the central issue in that experiment.) First, the experiment included only two extreme RCIs. Second, there was no evidence for reconfiguration in the results since CTI did not affect the size of the task-switching cost when the Response–Target Interval was kept constant. Specifically, switching cost was similar given a combination of a short RCI and long CTI, or a combination of a long RCI and short CTI. Finally, there was no evidence in Goschke's experiment that could support the interpreta-

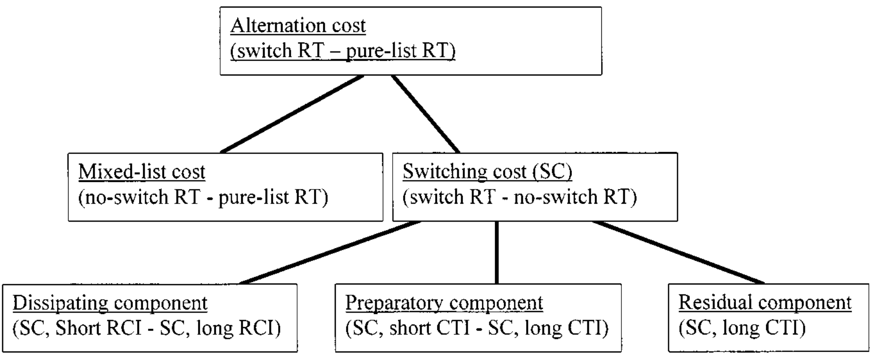

FIG. 16. Components of the task-switching cost (following Fagot, 1994, see text for details).

tion of the underlying process as nonstrategic. In other words, the reduction in switching cost due to increasing RCI may have resulted from active preparation.

The decomposition of switching cost into components is justified by the fact that these components are empirically dissociable; that is, affected by different sets of variables (e.g., Fagot, 1994, for similar points). Meiran (in press-a) suggested a detailed quantitative model which explains the empirical dissociations of the preparatory and the residual components of the switching cost by manipulating Congruency and Response-Repetition. Two predictions of the model concerning the differences between univalent and bivalent stimuli and responses were tested and confirmed by Meiran (in press-b). Specifically, Response-Repetition and Congruency affect the residual component of switching cost, but do not modulate the preparatory component. Like in previous studies, the current results indicate that Response-Repetition and Congruency interacted significantly with Task-Switch but the triple interactions including CTI were statistically insignificant. Rogers and Monsell (1995) found an analogous pattern of interactions concerning Congruency. The target stimuli in their experiments were digit-letter pairs, and the two tasks were odd–even and consonant–vowel judgements. They found somewhat larger switching costs when the irrelevant character was incongruent than when it was congruent, but this difference was not modulated by the preparatory interval. However, Fagot (1994) and Monsell et al. (1998) did not find larger switching costs in the incongruent condition than in the congruent condition. With respect to Response-Repetition, the present results are similar to those reported by Rogers and Monsell (1995) and by Fagot (1994). Finally, Congruency and Response-Repetition did not significantly affect the dissipating component as revealed by insignificant triple interactions involving RCI.

Although the preparatory component and the dissipating component were not dissociable with respect to Response-Repetition and Congruency, they were dissociable with respect to Practice. Session, CTI, and Task-Switch interacted significantly in Experiment 2 and in Meiran's (1996) Experiment 4. This interaction indicates that one session of practice affected only the preparatory component of switching cost, but left the residual component unchanged. This pattern did not replicate in Experiment 3 and the reasons should be explored in the future. Nonetheless, it seems that the results of Experiment 2 indicate the more common pattern. For example, the results of the young participants in Kramer et al.'s (1999) second experiment were similar to the present Experiment 2. Moreover, results from a yet unpublished experiment in our lab are also more similar to the present Experiment 2 than the present Experiment 3. We therefore conclude cautiously that limited practice usually affects the preparatory component of switching costs, at least when instructional cues are supplied. In contrast, similar levels of practice did not affect the dissipating component (Experiments 1 and 2, indicating an insignificant interaction between Session, RCI, and Task-Switch). Although practice effects on the preparatory component may depend on yet unexplored factors, this does not compromise our conclusions regarding a dissociation of the preparatory component and the residual component. In Experiment 2, the conditions permitted practice to reduce the preparatory component of switching cost. Yet, these conditions did not permit a similar reduction in the dissipating component in the same experiment. This may be taken as additional evidence that cost reduction by increasing RCI is not reflecting active preparation.

The fact that the pattern of interactions between practice, Response-Repetition, preparatory interval, Congruency and Task-Switch is similar in several studies suggests that task switching involves analogous processes in the various experimental paradigms. However, there seem to be important differences between the various experimental paradigms and these should be explored systematically in the future, to determine which processes are common to all paradigms, and which processes are paradigm-specific. The potential factors contributing to the differences include the tasks, the relative difficulty of the tasks (e.g., Allport & Wylie, in press), nature of cues (e.g., de Jong, 1997), and task ordering (random, fixed, etc.). We mention one important discrepancy between experimental paradigms. Fagot (1994, Experiment 8) conducted a study where the participants alternated between odd/even and higher-than-six/lower-than-six judgments of target digits. The paradigm was essentially the same as that in Sudevan and Taylor's (1987) study, except that Sudevan and Taylor did not include Task-Switch as an independent variable in their analyses. Although Sudaven and Taylor's results concerning an effect of CTI were replicated, Fagot did not find a significant interaction between CTI and Task-Switch. In other words, the task-switching cost was not significantly affected by preparation. Since RT was facilitated by increasing the CTI, the insignificant interaction between CTI and Task-Switch could not be interpreted as reflecting an unwillingness to engage in preparation (de Jong, in press). Apparently, the participants in Fagot's study did not engage in reconfiguration, as we define it, but engaged in general preparatory processes.

We wish to conclude by mentioning two important implications of the present findings and theoretical approach. First, task-switching cost should not be taken as an index of a single process. It certainly cannot be taken as a measure of executive functioning. There are several reasons for this conclusion. First, our results suggest that the dissipating component of switching costs does not reflect cognitive control. Furthermore, while the preparatory component reflects control success, the residual component reflects control failure or a lack of motivation to engage in control (de Jong's in press). Finally, the relationship between the preparatory component of switching costs and cognitive control seems to be complicated. For example, we conjectured that a small preparatory component sometimes reflects the fact that participants did not fully engage in the task in the previous trial. If so, a small preparatory cost component indicates little involvement of control. However, a small preparatory component may also indicate fast and efficient control. Undoubtedly, the preparatory component needs further exploration before its role in cognitive control is clear.

The second implication refers to the notion of preparation. Apparently, referring to preparation as a unitary process makes little sense in light of the findings that there is a variety of preparatory processes. Moreover, these processes may operate independent of one another as we have shown regarding phasic arousal, predicting target onset, and reconfiguration.

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