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Consciousness and Control in Task Switching

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Participants were required to switch among randomly ordered tasks, and instructional cues were used to indicate which task to execute. In Experiments 1 and 2, the participants indicated their readiness for the task switch before they received the target stimulus; thus, each trial was associated with two primary dependent measures: (1) readiness time and (2) target reaction time. Slow readiness responses and instructions emphasizing high readiness were paradoxically accompanied by slow target reaction time. Moreover, the effect of task switching on readiness time was an order of magnitude smaller then the (objectively estimated) duration required for task preparation (Experiment 3). The results strongly suggest that participants have little conscious awareness of their preparedness and challenge commonly accepted assumptions concerning the role of consciousness in cognitive control.

The relation between consciousness and human behavior has always been a central topic in cognitive psychology. Since the introspective analyses of Lotze (1852) and James (1890) and the early experimental work of Ach (1905), we know that many aspects of stimulus and response processing are not consciously accessible. Even stimulus–response translation, a process that was often thought to be under tight conscious control, seems to be carried out rather automatically (for overviews, see Hommel, 2000a, 2000b). However, there is broad consensus that higher level control operations—those operations that implement task sets by selecting, ordering, and chaining lower level task execution processes—are intimately linked to conscious awareness (e.g., Ach, 1905; Baars, 1987; Baddeley, 1996; Jacoby, 1991; James, 1890; Shallice, 1994; Tzelgov, 1997). The goal of the present experiments was to investigate how close this link really is. To anticipate the results, we found evidence for very poor conscious awareness regarding when task preparation has been completed.

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Although we do not deny the role of consciousness in performance in general, our results suggest that consciousness has an indirect role rather than a direct role in the type of cognitive control operation which we studied.

The particular control operation we focused on was the *implementation of task set* in the task-switching paradigm. This paradigm was widely explored by Jersild (1927) and has recently attracted scientific attention following the lead of Allport, Styles, and Hsieh (1994). In that paradigm, participants are required to rapidly alternate between two or more tasks. On some trials the task is repeated (*no-switch* trials), so that lesser degree of control operation is required, while on other trials the task changes (*switch* trials). Changing tasks is commonly associated with changes in the relevant stimulus dimension and/or the valid stimulus–response mappings. Therefore, the actor needs to prepare and implement a new task set—a process that is commonly assumed to be performed by cognitive control operations (Gopher, 1996; Logan, 1985; Monsell, 1996; Norman & Shallice, 1986). Indeed, the assumption that the preparation for task switching is tied to control operations is strengthened by several observations. These include the following: (1) switching performance is sensitive to manipulations that presumably affect strategic processing (Rogers & Monsell, 1995), (2) task preparation is proactive and specific to situations requiring a change in system reconfiguration (Meiran, 1996, 2000a, 2000b; Meiran, Chorev, & Sapir, 2000), (3) the efficiency of task preparation depends on motivational factors (De Jong, 2000), (4) preparation is accompanied by deliberate verbalization (Goschke, 2000), and (5) task preparation is linked to task decision (Fagot, 1994) and requires the loading of behavioral goals into working memory (Rubinstein, Meyer, & Evans, submitted).

The rationale of our study was based on the two assumptions elaborated above: (a) high-order control involves conscious awareness and (b) the preparation for a task switch is considered to be an example of a high-order control operation. Thus, it is reasonable to predict that participants would be aware when the preparation for a task switch begins and when it has been completed. In the present work, we concentrated on participants' awareness that preparation has been completed. Contrary to the initial predictions, our results suggest poor conscious monitoring of one's preparedness. Moreover, since participants seem to be unaware of their preparedness, when asked to indicate their readiness, their responses are based on correlated clues, such as estimated task difficulty.

In our paradigm, trials involving several tasks were pseudorandomly intermixed and, in each trial, participants were presented with a fully valid task cue instructing them which task to execute. Thus, there were both switch trials and no-switch trials. Previous studies have established that switch trials are associated with poorer performance compared with no-switch trials, indicating *switching cost* (e.g., Allport et al., 1994; Jersild, 1927).

In Experiments 1 and 2, participants were asked to prepare the indicated task as soon as the task cues appeared. Furthermore, they were asked to indicate when they felt that they were ready to perform the upcoming task. They did so by pressing a key (readiness response). The readiness response was followed by a target stimulus, which the participants were required to classify according to the relevant task rule. Thus, each trial involved two responses: a readiness response and a target response.

The readiness response (associated with *readiness time*) followed the task cues, while the target response (associated with reaction time, *RT*) was given after the presentation of the target stimulus.

In order to determine if participants were aware of their preparedness, we examined the relation between readiness time and RT. We originally considered two different potential relations between the measures. First, we reasoned that if participants are aware of their preparedness, and indicate their readiness only when optimally prepared, readiness times and RTs should be *unrelated within a given condition.* This is because, by holding the condition constant, we held constant the two potential sources of common variance: individual differences and differences between conditions. Second, participants may sometimes indicate their readiness prematurely or even without preparing at all (see De Jong, 2000, for evidence supporting this possibility). If so, longer readiness times (reflecting more complete readiness) would be associated with shorter RTs and perhaps smaller switching cost. Note that this possibility would not necessarily speak against conscious awareness of task preparation nor would it necessarily require such awareness, but only suggest some variability in the criterion used for judging readiness. Although we originally considered only the above-mentioned two potential relations, the results indicated a third relation, to be discussed more fully under Experiment 2. Thus, the fact that the first potential relation involves predicting a null hypothesis becomes less relevant.

General Method of the Present Study

Our experimental design was based on two studies by Dixon (1981) and Dixon and Just (1986). In the 1981 study, Dixon asked participants to perform binary choice reaction-time (RT) tasks on letters. Prior to the presentation of a letter, a task cue was presented, specifying how letters were mapped to responses. For example, the instructional cue, ‘‘X J’’ indicated a choice between ‘‘X,’’ requiring a left key-press, and ‘‘J,’’ requiring a right key press. After the presentation of the task cue, the participants indicated their readiness by lifting a pedal and a target letter (e.g., ‘‘X’’) was presented for a response. As in the present study, the two variables of interest were readiness time and RT. The current experiments were run because Dixon did not examine the relation between readiness time and RT in the manner that we did. Specifically, unlike Dixon, we examined the effects of trial-to trial task switching and examined RT as a function of readiness time.

In the present experiments, participants performed binary-choice discrimination tasks on target stimuli that varied along four perceptual dimensions: shape (circle vs square), size (small vs large), fill of the figure (empty vs full), and the tilt of a line crossing the figure (vertical vs horizontal). Each task required a speeded binary decision that was based on a single perceptual dimension such as fill or shape. A trial began with the presentation of a task cue. We used the same type of cues as Meiran (1996, Experiment 5) because they are conceptually similar to the cues used by Dixon (1981). In both cases, the position of the stimulus values indicated the position of the corresponding response keys. That is, the symbol presented on the right side represented the stimulus requiring a right-hand key press, while the symbol on the left side indicated the stimulus requiring a left-hand key press. For example, the instructional cue for the shape task consisted of a circle on the right and a square on the left, this way indicating a right key press to circles and a left key press to squares.

Since Dixon (1981) found that the number of alternative tasks affected readiness time, we also varied the number of tasks. There were three groups of participants in each experiment. These groups alternated between two, three, or four tasks. We also counterbalanced the combination of tasks between which participants switched. Manipulating Number-of-Tasks introduced a few confounding variables. First, an increase in the Number-of-Tasks was confounded with the probability of a task repetition; with two tasks, the probability that the task will repeat itself in the next trial is .5. However, with four tasks this probability is only .25. To solve this problem, task order was not random. Instead, the probability of task repetition/switch was set to .5 in all cases. In the case of a task switch, one of the remaining tasks, which had not been just performed, was chosen at random. Second, increasing Number-of-Tasks resulted in fewer trials per task. In order to solve this problem, the data were submitted to two sets of analyses. The main set of analyses were performed on the entire data set, where the conditions were equated with respect to experiment length, but the Number-of-Tasks was confounded with the number of trials per task. A secondary set of analyses was performed on the first 180 trials of a given task. The number 180 was chosen because this was the minimal number of trials per task, i.e., in the four-task condition. Note that in the second set of analyses, Number-of-Tasks was confounded with experiment length but not with trials per task. Thus, if the main effect of Number-of-Tasks, or interactions with that variable, are found significant in both analyses, one can be reasonably certain the effects did not result from differential practice or differential experiment lengths. However, when the effect of Number-of Tasks was significant in the full data set but not in the partial data set, as happened in a few cases, this suggested that the effect resulted from differential practice rather than from Number-of-Tasks per se.

EXPERIMENT 1

Experiment 1 consisted of a conceptual replication of Dixon's (1981) experiment. For the reasons outlined above, we were mainly interested in the effects of Task-Switch and Number-of-Tasks on readiness time, RT, and the relation between these two measures. Whatever the basis for participants to judge their readiness, we expected readiness time to increase with Number-of Tasks (replicating Dixon, 1981) and be larger if a task switch was required. The latter prediction is not unique to a given interpretation because, on the one hand, it may result from the fact that (a) participants are aware of their preparedness and (b) more preparation is required in the switch condition than in the no-switch condition (e.g., Meiran, 1996). On the other hand, a similar prediction may be made assuming that readiness time is based on estimated task difficulty rather than actual awareness of preparedness. Of course, the latter interpretation is based on the (reasonable) assumption that participants estimate the switch condition as being more difficult than the no-switch condition.

We also predicted an effect of task switching on RTs. This may be surprising because one may argue that no task-switching costs should occur if preparation for a task is optimal. However, recent findings strongly suggest that switching costs do not only depend on the degree and duration of task preparation. Costs are also affected by proactive aftereffects of the previous task. This has been demonstrated to produce task-switching costs even with perfect preparation (e.g., Fagot, 1994; Gotler & Meiran, 2000a, 2000b; Meiran et al., 2000; Rogers & Monsell, 1995).

More important was the analysis of the relations between readiness time and RT. When we analyzed RT as a dependent variable, we added relative readiness time as an independent variable, hence Readiness-Time-Bin. To create that variable, readiness time was divided into four bins with equal number of trials. These corresponded to the 25% shortest, next shortest, next longest, and longest readiness times. As already pointed out, no effect of Readiness-Time-Bin on RTs or task-switching costs would be expected if participants were aware of their readiness state *and* obeyed the instructions. A negative relation (i.e., faster RTs with longer readiness times) would indicate that participants do not always wait until they are fully prepared before pressing the ready key.

Method

Participants. Thirty-six undergraduate students from the Ben-Gurion University of the Negev participated for a partial course credit. They were evenly divided among the three groups. To control for task combination, three participants in the three-tasks group were assigned to each of the four possible task triads. Similarly, two participants in the two-task group were assigned to each of the six possible task dyads.

Stimuli and apparatus. All testing was conducted in front of an IBM 286 clone controlled by software written in MEL 1.0 language (Schneider, 1988). Target stimuli were presented in white on a black background in the middle of the screen and varied along four dimensions. These stimuli were either a small/large circle (with a diameter subtending a visual angle of approximately 1.4° or 3.0°) or a small/large square (each side subtending 1.4° or 3.0°) that was either empty (only the circumference depicted in white on black) or filled (the entire figure filled with a light gray color). A line which subtended 4.5° crossed the figure in its middle and was either horizontal or vertical.

The instructional cues were pairs of figures presented 4.5° to the right and to the left of the middle of the screen, measured to the center of the figures so that, when the target stimulus was presented, it was seen in between the right and left parts of the instructional cue. The cues for the shape task were a circle (diameter of 2.2°) on the right and a square (one edge subtending 2.2°) on the left. The cues for the fill task were a shape composed of a square (one edge subtending 1.9°) and a circle (diameter of 2.2°) superimposed on it such that the cue on the right was empty (the outlines of both the circle and the square were seen in white on black), and the cue on the left was filled in white. The cues for the tilt task were a line subtending 1.9° which was horizontal on the right side and vertical on the left side. Finally, the cues for the size task were also an overlapping square and a circle. The large figure was presented on the left and was composed of a circle of a diameter of 3.5° and a square with a side of 2.5°. On the right the small figure was presented. The diameter of the circle was 1.4° and a side of the square subtended 1°. The participants responded by

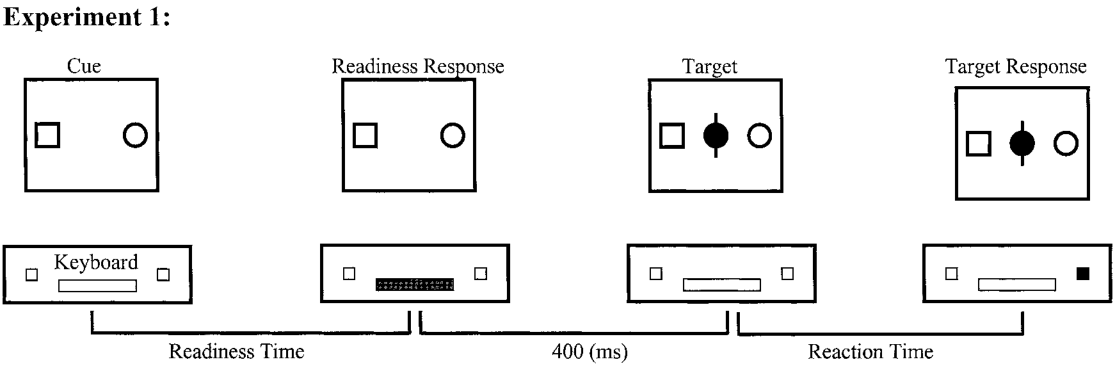

FIG. 1. A schematic description of an experimental trial in Experiment 1.

pressing the ‘‘/’’ key on the right and the ‘‘Z’’ key on the left and RT was measured to the nearest 1 ms (Fig. 1).

Procedure

The experiment consisted of a single 1-h session. The session began with detailed written instructions presented by the computer, followed by some practice (30 trials), followed by four identical blocks of 180 trials each. The probability for a task switch was equated across conditions in the following manner. In each trial, it was first determined if it would involve a task switch ($p = .5$) or a task repetition. In the case of task repetition, the same task as in the previous trial was chosen. In the case of a task switch, if there were only two tasks, the task that was not executed in the previous trial was chosen. If there were three or four tasks, and a task switch was indicated, one of the remaining task(s) was chosen randomly with equal probability. The participants rested their index fingers on the two keys, ‘‘/’’ on the right and ‘‘Z’’ on the left, and rested their thumbs on the spacebar. Their task was to indicate, by a key press, the identity of the target stimulus along one of four dimensions: shape (circle vs square), fill (empty vs full), size (small vs large), and the tilt of a line crossing the figure (vertical vs horizontal). An instructional cue that preceded the target stimulus indicated the relevant task.

A trial consisted of (1) the presentation of the instructional cue; (2) the pressing of the spacebar with the thumbs, indicating that the participant was ready; (3) a constant interval of 400 ms during which only the instructional cues were presented; (4) the presentation of the target stimulus along with the instructional cue until the response; and (5) the clearing of the screen for an inter-trial interval of 2100 ms. The intertrial interval was determined on the basis of results by Meiran et al. (2000), that indicated that the task switching cost is reduced during the first second after responding. The target stimuli were selected randomly. For each participant, only those dimensions that could be task-relevant changed while the remaining dimensions were constant. If size discrimination was not a task, all targets were small; if shape discrimination was not a task, all the shapes were circles; if tilt discrimination was not a task, the line crossing the figure was always horizontal; and if fill discrimination was not a task, all shapes were empty.

Analytic procedures. The no-switch condition included only the first repetition of a task. Responses preceded by errors or by RTs greater than 3000 ms were excluded from all analyses. We chose the value 3000 ms because more prolonged RTs and readiness times were very rare. Accordingly, RTs and readiness times greater than 3000 ms and RTs corresponding to errors were replaced by missing values and, thus, were analyzed for accuracy only. Outliers were defined as RTs falling outside the untrimmed mean $\pm$ 2 untrimmed SDs. These outliers were replaced by the untrimmed mean of the specific condition for a given participant. Untrimmed means and SDs were separately computed for each experimental condition and participant.

Results and Discussion

Alpha level was set at .05 in all analyses.

Readiness time. The mean number of nonmissing observations per condition for a given participant ranged between 165 and 344. The large range reflects the fact that there were more observations in the switch condition than in the no-switch condition, where only the first repetition of the task was considered. In the full data set, mean readiness times in the switch condition were 366, 446, and 494 ms in the two-, three-, and four-task conditions, respectively. In the no-switch condition, mean readiness times were 362, 430, and 460 ms in the two-, three-, and four-task conditions, respectively.

Two independent variables were included in the 3 $\times$ 2 analysis of variance (ANOVA): Number-of-Tasks (between participants) and Task-Switch (within participants). The main effect of Task-Switch was significant, $F(1, 33) = 15.00$, $MSE = 397.25$, reflecting longer readiness times in the switch condition (435 ms) than in the no-switch condition (417 ms). Thus, the average effect of Task-Switch on readiness time was significant, but surprisingly small, 18 ms. The main effect of Number-of-Tasks was only marginal, $F(2, 33) = 3.22$, $p = .052$, $MSE = 24409.08$, and did not approach significance in the analysis of the partial set. Nonetheless, the trend was retained, albeit being numerically smaller (full set: 364, 438, and 477 ms; partial set: 399, 457, and 477 ms; for two, three, and four tasks, respectively). The discrepancy between the two analyses (full vs partial data set) suggests that the effect of Number-of-Tasks on readiness time is attributable (in part) to the fact that increasing Number-of-Tasks resulted in less practice on any given task. This, in turn, resulted in faster readiness times when there were fewer tasks.

The interaction between Number-of-Tasks and Task-Switch was significant, $F(2, 33) = 3.36$, $MSE = 397.25$, in both analyses. Separate analyses indicated that the simple main effect of Task-Switch was statistically significant for three and four tasks but not for two tasks, where it was not only unreliable but also tiny (4 ms). The results concerning the simple main effect of Number-of-Tasks depended on whether the full or partial set was analyzed. In the full set, Number-of Tasks was significant in the switch condition and marginal ($p = .07$) in the no-switch condition. In contrast, neither simple effect was significant in the partial set.

Our results replicated those by Dixon (1981) in showing some indication of an increase of readiness time with an increasing number of tasks. However, it is difficult to draw strong conclusions since the effect was rather small, unreliable, and resulted, in part, from the differential practice on a given task, associated with Number-of-Tasks. More reliable was the increase in readiness times associated with task switching found when participants were given three or four tasks. The latter effect indicates that readiness times increase with preparation demand. As mentioned above, this result is not indicative of participants' awareness of their preparedness. At the present stage, we only wish to draw readers' attention to the small size of the effect, only 18 ms, on average, and 4 ms in the two-tasks condition.

Reaction time. Mean RTs are presented in Table 1. The mean number of non missing observations per condition for a given participant ranged between 40 and 90. We also included the range of readiness times corresponding to each bin. The values are the mean first, second, and third within-cell readiness-time quartiles. The reader should keep in mind that trials were partitioned to bins for each condition, separately. In other words, the quartile values represent means of the cutoffs actually being used.

The ANOVA included Task-Switch, Number-of-Tasks, and Readiness-Time-Bin as independent variables. There were three reliable effects. First, RTs were longer in task-switch trials (515 ms) than in no-switch trials (501 ms), $F(1, 33) = 5.75$, $MSE = 2293.71$, indicating switching cost of 14 ms on average. The size of task-switching cost is similar to what is often being found in the cueing version of the task-switching paradigm (e.g., Meiran, 1996). Moreover, the presence of switching cost supports previous conclusions concerning the limitation of preparation for a task switch (Fagot, 1994; Meiran et al., 2000; Rogers & Monsell, 1995). Interestingly, in the two-task and four-task conditions, noticeable task-switching cost were only observed with short readiness times, that is, when participants readiness responses were in the first bin, $F(1, 22) = 4.80$, $MSE = 894.15$ ($p = .10$, in the partial set). Furthermore, a planned contrast indicated that the difference in task-switching cost between the fastest bin of readiness times and slower readiness times was also significant ($p = .08$ in the partial set). A possible reason for this result could be that preparation was not always completed when the readiness signal was given.

Second, and most importantly, the main effect of Readiness-Time-Bin was significant, $F(3, 99) = 32.63$, $MSE = 1550.85$, indicating an *increase* of RT with increasing readiness time. This result clearly refutes our predictions concerning either a null effect or negative relation between readiness time and RT.

Finally, there was a marginally significant effect of Number-of-Tasks, $F(2, 33) = 3.09$, $p = .055$, $MSE = 138578.19$, indicating an increase of RT with more tasks, from 435 ms with two tasks and 521 ms with three tasks to 567 ms with four tasks. Although the omnibus test failed to reach significance, the linear trend was significant, $F(1, 33) = 5.99$, $MSE = 138578.19$, and the deviation from linearity was nonsignificant, $F < 1$. Given the higher memory load with more tasks, this effect is not surprising. Interestingly, however, there was no hint of an interaction with task switch. The last result is at odds with what one would expect from executive-controller models like those of Norman and Shallice (1986). This model assumes direct competition between task schemata, which suggests an increase in control de-

TABLE 1
Responses to Target Stimuli: Mean RT (ms) and Percent Error (PE)—Experiment 1

Readiness-time bin		Two tasks			Three tasks			Four tasks		
		S	NS	Cost	S	NS	Cost	S	NS	Cost
1	RT	415	402	13	502	474	28	540	514	26
	PE	.08	.07	.01	.05	.07	.02	.09	.08	.01
Q1		263	262		320	320		368	347	
2	RT	431	432	−1	521	496	25	564	560	4
	PE	.00	.00	.00	.00	.00	.00	.00	.00	.00
Q2		338	332		410	397		455	424	
3	RT	444	442	2	551	524	27	587	577	10
	PE	.00	.00	.00	.00	.00	.00	.00	.00	.00
Q3		450	450		552	528		605	554	
4	RT	460	457	3	567	536	31	593	599	−6
	PE	.00	.00	.00	.00	.00	.00	.00	.00	.00

Note. S, Switch, NS, No-Switch; Readiness-Time Bin: 1=25% fastest, 2=25% next fastest, 3=25% next slowest, 4=25% slowest. Q1 is the mean first readiness-time quartile, which served as Bin 1-Bin2 cutoff. Q2 is the mean median readiness-time, saving as the Bin2-Bin3 cutoff. Q3 is the mean third readiness-time quartile, serving as the Bin3-Bin4 cutoff. Values concerning Q1, Q2, and Q3 represent readiness times (mean cutoff values), while the remaining values represent target RTs and PEs.

mands with an increasing number of active tasks. Accordingly, switching costs, which are commonly believed to reflect control demands, should be higher as the number of tasks increases. Obviously, this is not what we have observed.

Errors

Errors were only committed when readiness responses were in the fastest bin. An ANOVA on errors in this bin according to Task-Switch and Number-of-Tasks indicated no significant source of variation. This finding could suggest that preparation was not always completed when the readiness response was given.

EXPERIMENT 2

The results of Experiment 1 were surprising. Most notable was the fact that RT *increased* with increasing readiness time. This result clearly contradicts the predictions made under the assumption that participants are aware of their preparedness. Taken together with the fact that switching tasks had only a tiny effect on readiness time, the results suggest that participants had poor awareness of their preparedness.

The explanation we suggest is that participants are unaware of their preparedness and therefore, when asked to indicate it, guess based on indirect information, such as perceived task difficulty (e.g., a task switch and number of tasks). Analogous strategies were reported in studies on meta-cognition. For example, participants base their recognition responses on word identification fluency (e.g., Whittlesea, 1993). Similarly, feeling of knowing judgements are based on the ease of information retrieval (Koriat, 1993). Thus, the effect of task switching on readiness time reflects, according to our explanation, the fact that participants perceive the switch condition as more difficult than the no-switch condition.

Critically, our explanation implies that readiness responses should not be treated as reflecting readiness for the upcoming task but, in a sense, as representing a separate task. That is, a readiness response and the following target response might be best conceptualized as a pair of relatively independent trials rather than as two parts of a single trial. Such a position has important empirical implications. In a series of experiments, Strayer and Kramer (1994) found evidence for poor dynamic control of speed–accuracy trade-off. Changes in the trade-off were brought about gradually over a series of trials, which implies that trials which are adjacent in a sequence are associated with a similar speed–accuracy trade-off. In other words, an emphasis on speed or accuracy in Trial N-1 ‘‘spills over’’ to Trial N so that their RTs are positively correlated.

We applied this reasoning to Experiment 1 and assumed that a given readiness response and the following stimulus-triggered response are just two unrelated but successive reactions. This assumption made it possible to explain the positive relation between readiness time and RT. Indeed, one aspect of our results supports this interpretation. Note that, in Experiment 1, errors in responses to target stimuli were only observed when readiness time was very short. One interpretation is that fast readiness responses indicate lesser readiness and consequently resulted in more errors. Yet, there are two reasons to doubt this account. First, lesser readiness should have produced slower responses, rather than faster responses, as we have found. Second, the increased error rate in the fastest bin of readiness time should have been restricted to the switch condition, where reconfiguration was needed most. However, this trend of higher error rate in the switch condition was zero on average. In conclusion, we attribute this effect to an emphasis on speed (in readiness responses) that spilled over to target responses, which were therefore both fast and inaccurate.

To test the notion of a ‘‘spillover’’ of speed–accuracy criteria, we manipulated readiness time directly in Experiment 2. There were two conditions, each with a different speed–accuracy instruction. In the *high-readiness* condition, participants were instructed to indicate their readiness only when they felt completely ready. In contrast, the instructions in the *low-readiness* condition were to indicate readiness as quickly as possible even when not being fully ready. Trivially, readiness instructions were predicted to affect readiness time. The interesting question was whether the different emphasis on speed or accuracy in the ‘‘readiness part’’ of the task would spill over to the ‘‘target response’’ part of the task. In fact, based on our tentative hypotheses, we predicted that emphasizing high readiness would, somewhat paradoxically, result in prolonged (although more accurate) target responses. Note that awareness of one’s readiness state, coupled with premature readiness responses, is predicted to cause fast readiness responses to be associated with slow RT. In other words, the experiment contrasted between two opposite predictions. If participants are aware of their readiness state, RT is predicted to be faster in the high-readiness condition. In contrast, if participants are unaware of their preparedness, RT is predicted to be longer in the high-readiness condition.

We also took the opportunity to introduce a procedural change. The conditions in Experiment 1 allowed participants to postpone preparation until after the readiness response. The reason is that first, the instructional cues remained visible until the response to the target. Moreover, the target stimulus was presented 400 ms after the readiness response, so that the empty interval could be used for further preparation. Therefore, in Experiment 2, the instructional cues were removed from the display as soon as the target stimulus was presented. Gotler and Meiran (in press) found that removing the instructional cues in this manner resulted in more advanced preparation. In addition, the target stimulus was presented as soon as readiness was indicated, that is, the 400 ms delay was taken out. This meant that participants were less likely to postpone preparation until after the readiness response.

Method

Participants. Thirty-six students from Ben-Gurion University of the Negev took part in the present experiment and were assigned to conditions as those used in Experiment 1.

Stimuli and procedure. There were only a few procedural modifications to Experiment 1 (see Fig. 2). First, the task cues were deleted as soon as the participant indicated readiness, and at the same time, the target stimulus was presented until the response. After 20 practice trials, participants were presented with eight blocks of 90 trials each, with the blocks differed with respect to speed–accuracy instructions, which were presented before each block. One set of instructions emphasized complete readiness (Condition A), and the other instructions emphasized high speed in the readiness response (Condition B). The two conditions were counterbalanced within participants by means of an ABBA–BAAB ordering of the experimental blocks.

Experiment 2:

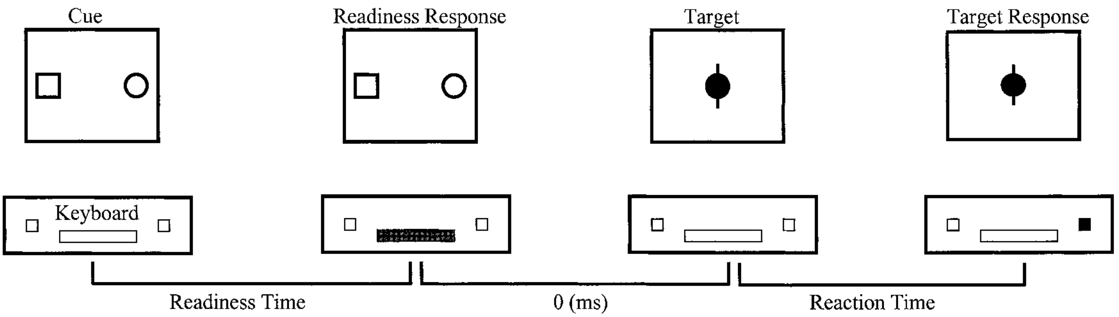

FIG. 2. A schematic description of an experimental trial in Experiment 2.

Results

Because of the speed–accuracy trade-off manipulation and the associated counterbalancing scheme, it was no longer possible to equate the groups in terms of the number of times each task was executed, and a single analysis (on the complete data set) was performed on each of the two measures. This limitation turned out to be unimportant because the effect of Number-of-Tasks on readiness time did not replicate and because our main concern was the relation of readiness time and RT.

Readiness time. There were between 81 and 175 trials per condition, on average. Readiness times were submitted to a 3 × 2 × 2 ANOVA according to Number-of-Tasks, Readiness-Instructions (high/low), and Task-Switch. The corresponding means are presented in Fig. 3.

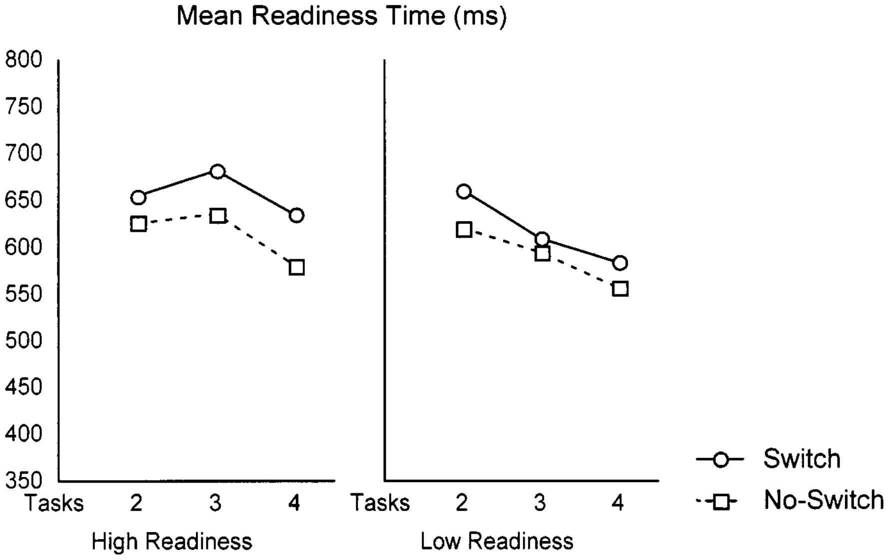

FIG. 3. Mean Readiness Time (in milliseconds) as a function of Condition in Experiment 2.

There were only two significant main effects: Task-Switch, $F(1, 33) = 19.12$, $MSE = 2543.85$, and Instructions, $F(1, 33) = 6.97$, $MSE = 13695.31$. None of the remaining sources of variance approached significance. These results indicate that readiness responses were faster in the no-switch condition (601 ms) than in the switch condition (638 ms). Like in Experiment 1, the effect of task switching on readiness time (37 ms, on average) was rather small. Importantly, readiness responses were faster in the low-readiness condition (594 ms) than in the high-readiness condition (645 ms, an effect of 51 ms). In other words, the instruction manipulation actually worked. Interestingly, mean readiness time was longer in this experiment (620 ms on average) than in Experiment 1 (426 ms), suggesting that, as expected, the procedural changes were effective in causing participants to postpone their readiness responses. Note that, unlike in Experiment 1, there was not even a numerical trend for increasing readiness time with more tasks, which supports our suspicion that the effect is not very reliable.

Reaction time. The means are presented in Table 2; there were between 15 and 50 observations per condition, on average.

The data were submitted to a $3 \times 2 \times 4 \times 2$ ANOVA with Number-of-Tasks, Instruction, Readiness-Time-Bin, and Task-Switch as independent variables. The main effect of task-switch was significant, $F(1, 33) = 9.08$, $MSE = 10348.45$, indicating faster responses in the no-switch condition (543 ms) compared with the switch condition (569 ms; switching cost = 26 ms). Moreover, as in Experiment 1, RT increased with increasing readiness time, $F(3, 99) = 31.40$, $MSE = 5411.82$ (535, 533, 549, and 606 ms in Bins 1 through 4, respectively), despite the modified procedure. Most importantly, there was a significant main effect of Instruction, $F(1, 33) = 6.81$, $MSE = 5801.93$. As predicted, responses to the target stimulus were *faster* in the low-readiness condition (547 ms) than in the high-readiness condition (564 ms, an effect of 17 ms). Evidently, the set for speed or accuracy adopted in the ‘‘readiness part’’ of the task spilled over to the ‘‘reaction part.’’

Errors. A similar ANOVA was performed on the proportion of errors. It revealed significant main effects of Readiness-Time-Bin, $F(3, 99) = 8.13$, $MSE = .0023$, and of Instruction, $F(1, 33) = 5.05$, $MSE = .0017$, and a significant interaction between Number-of-Tasks and Task-Switch, $F(2, 33) = 3.69$, $MSE = .005$. Unlike in Experiment 1, there were errors in all readiness time bins, with the rates decreasing from bin 1 through 3 (.06, .04, and .03) and increasing again in bin 4 (.05). As expected, the raw trend indicated that participants were *less* accurate in the low-readiness condition (.05) than in the high-readiness condition (.04). The task switching cost in errors was zero in the two-tasks condition, $-.01$ in the three-tasks condition, and .01 in the four-tasks condition.

Discussion

The results were as predicted. The procedural changes caused participants to delay their readiness responses, which were considerably longer than in Experiment 1. It is interesting to note that this delay was also accompanied by a delay in target responses, relative to Experiment 1, which provides further support for our account. That is, relative to Experiment 1, in Experiment 2 there was a shift toward slow readiness

TABLE 2
Responses to Target Stimuli: Mean RT (ms) and Percent Error (PE)—Experiment 2

Readiness instructions	Readiness-Time Bin		Two tasks			Three tasks			Four tasks		
			S	NS	Cost	S	NS	Cost	S	NS	Cost
High readiness	1	RT	553	536	17	592	521	71	546	496	50
		PE	.04	.04	.00	.04	.04	.00	.09	.07	.02
	Q1		493	477		479	456		474	452	
	2	RT	543	548	−5	579	533	46	543	526	17
		PE	.04	.02	.02	.03	.02	.01	.08	.02	.06
	Q2		615	592		603	559		606	582	
	3	RT	560	543	17	574	565	9	547	541	6
		PE	.02	.03	−.01	.02	.04	−.02	.04	.05	−.01
	Q3		813	758		817	791		903	812	
	4	RT	609	614	−5	657	613	44	605	590	15
		PE	.02	.01	.01	.05	.04	.01	.08	.06	.02
Low readiness	1	RT	543	532	11	558	506	52	535	502	33
		PE	.05	.06	−.01	.04	.06	−.02	.08	.09	−.01
	Q1		471	461		457	444		412	401	
	2	RT	526	525	1	531	508	23	537	493	44
		PE	.02	.02	.00	.02	.02	.00	.07	.08	−.01
	Q2		572	564		556	528		516	494	
	3	RT	538	537	1	554	540	14	564	525	39
		PE	.02	.02	.00	.02	.02	.00	.06	.03	.03
	Q3		729	700		744	680		700	645	
	4	RT	583	574	9	651	585	66	617	576	41
		PE	.03	.03	.00	.05	.07	−.02	.09	.08	.01

Note. S, Switch; NS, No-Switch; Readiness-Time Bin: 1=25% fastest, 2=25% next fastest, 3=25% next slowest, 4=25% slowest. Q1 is the mean first readiness-time quartile, which served as Bin1-Bin2 cutoff. Q2 is the mean median readiness-time, saving as the Bin2-Bin3 cutoff. Q3 is the mean third readiness-time quartile, serving as the Bin3-Bin4 cutoff. Values concerning Q1, Q2, and Q3 represent readiness times (mean cutoff values), while the remaining values represent target RTs and PEs.

responses, which spilled over to target responses and made them slower as well. Importantly, the positive relation between readiness time and RT was replicated. However, unlike in Experiment 1, readiness time was not only measured but also manipulated. Changing emphasis from low readiness to high readiness increased readiness time, but critically, it also increased RT and decreased error rate in target responses. These results fully confirm the notion of ‘‘spillover’’ of speed emphasis from the readiness responses to target responses. In other words, hasty readiness responses were followed by hasty target responses, which were both faster and less accurate. In addition, the change in error rate due to readiness instructions was numerically larger in the no-switch condition (3.6% errors in the high readiness condition vs 4.9% errors in the low readiness condition) as compared to the switch condition (4.4 and 4.7% errors, respectively). Note that if the readiness responses reflected being ready for the task, one would have predicted the opposite trend, namely that instructions would influence accuracy in the switch condition more than in the no-switch condition.

The last analysis helps in ruling out an alternative explanation. That is, one could argue that participants understood the instructions as referring to accuracy rather than speed. This explains why high readiness instructions resulted in slower but more accurate responses. However, this explanation fails to account for the tiny effect of task switching on readiness time and also fails explaining why instructions had a larger effect in accuracy in no-switch trials than in switch trials.

EXPERIMENT 3

Given the results of Experiments 1 and 2, we have good reasons to assume that participants have poor conscious awareness of their task preparedness. The only indication of awareness regarding preparedness was the effect of task switching on readiness time. However, in order to interpret this effect as reflecting awareness of preparedness, the effect of task switch on readiness time should resemble the actual lengthening of preparation associated with task switching. Although we already suspected that the effect of task switching on readiness times was too small to reflect the actual difference in preparation time between switch trials and no-switch trials, we wished to base our suspicion on solid grounds.

Accordingly, the principal goal of Experiment 3 was to obtain an objective estimate of task preparation time. Thus, instead of letting participants determine preparation time, we manipulated preparation time by varying the *Cue-Target Interval* (CTI). Objective task-preparation time was estimated in two different ways. First, task switching cost is commonly assumed to comprise several components (e.g., Fagot, 1994; Meiran, 1996, 2000a, 2000b; Meiran et al., 2000; Rogers & Monsell, 1995). Only one component of switching cost is *preparatory*, reflecting processes that can be carried out during preparation or, more specifically, between task cue and target stimulus. Accordingly, our first estimate of preparation is the size of the preparatory component of switching cost. This component is estimated by the difference in switching cost between the shortest CTI and the longest CTI.

Our second estimate of task-preparation time is based on the function relating switching cost to CTI. Specifically, we computed, for each CTI, the corresponding switching cost C_i ($RT_{switch} = RT_{no\text{-}switch}$). As previous studies have shown, C_i decreases with increasing CTI (i.e., $C_n < C_{n-1}$; e.g., Meiran, 1996; Rogers & Monsell, 1995), hence preparation gets better over time. At some point, however, there is no further reduction in switching cost (i.e., $C_n = C_{n-1}$), indicating that preparation has come to an end. Accordingly, our second estimate of preparation time is CTI_n, namely the CTI after which switching cost is no longer reduced. There is a problem associated with the second estimate, since it is reasonable to suspect that cue processing involves stages of purely perceptual processing. The duration of these stages is yet unknown, but a crude estimate can be made based on Moulden et al.'s (1998) study using event-related potentials (ERPs). These researchers found that the difference between switch and no-switch conditions in cue processing was associated with several ERP components. The component that is most relevant for the present focus appeared 200 ms after the presentation of the task cue and its maximum was observed over the two occipital lobes, which are believed to carry out perceptual processes. For this reason, the minimal CTI we used was not zero but 110 ms.

Thus, we suggested two different estimates of objective preparation time. At present, it is unimportant to decide between these estimates. Critically, we were interested to determine whether the effect of task switching on readiness time (estimated as 18–37 ms in Experiments 1 and 2) reflected participants' awareness of their preparedness. If it does, we would expect that objective task-preparation time would lie close to 18–37 ms as well.

Our secondary goal was to validate our interpretation of RT switching cost in the previous experiments as reflecting residual switching cost. Residual cost refers to the fact that most studies have obtained substantial switching cost even at the longest preparation (Meiran, 1996, 2000a; Rogers & Monsell, 1995; see also Los, 1999). If our interpretation is correct, switching cost in the longest CTI should be close to the RT switching cost observed in Experiments 1 and 2.

In Experiment 3, we also addressed the fact that in Experiments 1 and 2, Number-of-Tasks was confounded with the number of irrelevant stimulus dimensions. We therefore ran two versions of Experiment 3. In Experiment 3a, the target stimuli varied along all four dimensions despite the fact that, for some participants, not all the dimensions were relevant. For example, tilt varied for participants whose task combination did not involve tilt discrimination, namely in some stimuli the line was horizontal and in other stimuli it was vertical despite the fact that line was irrelevant to any of the tasks. This implies that there was an inverse relation between Number of-Tasks and the number of irrelevant stimulus dimensions. Since there were only four stimulus dimensions and each task was related to a separate dimension, the greater the number of task, the smaller the number of irrelevant dimensions. Therefore, in Experiment 3b (which was similar to Experiments 1 and 2 in that respect), the stimuli varied only along the relevant dimensions and were constant along the irrelevant dimensions. This introduced a positive correlation between the number of tasks and the number of possible target stimuli in Experiment 3b. That is, with two tasks, there were only 4 (2×2) target stimuli; with three tasks, 8 stimuli ($2 \times 2 \times 2$); and with four tasks, 16 stimuli ($2 \times 2 \times 2 \times 2$). Therefore, Experiment 3b compensated for the confounding variables in Experiment 3a and vice versa. As in the previous experiments, number of tasks was confounded with the amount of practice on each task. Thus, we analyzed both the full data set and the partial data set including the first 180 executions of a given task.

Method

Participants. In each of Experiments 3a and 3b, six participants switched between four tasks and six participants switched between two tasks, one per possible task dyad. However, there were eight participants who switched between three tasks, two in each of the four possible dyads (a total of 20 participants per experiment; 40 in both experiments). This was done to ensure equal representation of tasks in the conditions.

Stimuli and procedure. The stimuli, number of blocks, and number of trials were identical to those used in Experiment 1. The participants rested their index fingers on the ''/'' and ''Z'' keys. A trial consisted of (1) the presentation of the instructional cue for a variable CTI of 110, 310, 710, or 1510 ms; (2) the presentation of the target stimulus along the instructional cue until the response; and (3) a blank screen for an intertrial interval of 1100 ms. This value was chosen based on results by Meiran et al. (2000) indicating relatively fast but passive dissipation of the previous task set (seen in a reduction in switching cost) during the first second after the response. The CTIs were selected on a random basis with equal probabilities, while the procedure for task selection and target-stimulus selection was as described in Experiments 1 and 2. In Experiment 3a, the target stimuli varied along all four dimensions even for those participants for whom the dimensions were irrelevant. In Experiment 2b, only those dimensions that were task relevant varied while the remaining dimensions were constant as in Experiments 1 and 2 (Fig. 4).

Results

The relevant means (taken from the full data set) are presented in Table 3; the mean number of observations per condition per participant ranged between 38 and 95.

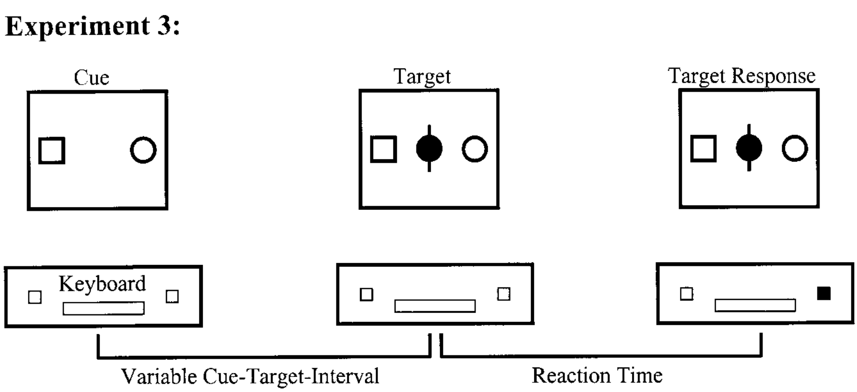

FIG. 4. A schematic description of an experimental trial in Experiments 3a and 3b.

TABLE 3
Mean RT (ms) and Percent Error (PE)—Experiments 3a and 3b[a]

		CTI (ms)	Two tasks			Three tasks			Four tasks		
			S	NS	Cost	S	NS	Cost	S	NS	Cost
Experiment 3a	RT	110	770	675	95	785	623	162	886	756	130
	PE		.02	.01	.01	.03	.03	.00	.02	.00	.02
	RT	310	670	598	72	663	555	108	743	681	62
	PE		.01	.03	−.02	.03	.02	.01	.03	.02	.01
	RT	710	618	581	37	588	578	10	588	570	18
	PE		.02	.02	.00	.03	.02	.01	.02	.02	.00
	RT	1510	593	572	21	571	561	10	618	574	44
	PE		.02	.02	.00	.03	.03	.00	.01	.03	−.02
Experiment 3b	RT	110	756	666	90	889	696	193	892	719	173
	PE		.03	.01	.02	.02	.01	.01	.03	.01	.02
	RT	310	711	631	80	737	628	109	747	640	107
	PE		.03	.02	.01	.01	.00	.01	.02	.01	.01
	RT	710	652	637	15	665	583	82	610	562	48
	PE		.02	.01	.01	.01	.01	.00	.02	.02	.00
	RT	1510	644	632	12	670	619	51	560	558	2
	PE		.03	.02	.01	.02	.00	.02	.02	.01	.01

[a] S, Switch; NS, No Switcg; CTI, Cue-Target Interval.

Reaction time. The ANOVA was 2 × 3 × 4 × 2 with Experiment (3a vs 3b) and Number-of-Tasks (two or four) as between-participants independent variables and CTI (110, 310, 710, and 1510 ms) and Task-Switch (switch vs no-switch) as within-participant independent variables. Importantly, Experiment was not involved in any significant source of variation.

The two significant main effects included CTI, $F(3, 102) = 57.29$, $MSE = 7786.74$, and Task-Switch, $F(1, 34) = 97.36$, $MSE = 4495.81$. Critically, the expected interaction between CTI and Task-Switch was significant, $F(3, 102) = 27.51$, $MSE = 2220.78$. It indicated a marked reduction in switching cost as a result of preparation from 164 ms in the shortest CTI to only 23 ms in the longest CTI. This interaction was neither qualified by Experiment nor by Number-of-Tasks, as indicated by insignificant triple interactions with these variables. Thus, the size of preparatory cost, which is our first estimate of task preparation time, was $164 - 23 = 141$ ms.

Although switching cost was reduced, it was not eliminated and was significant even in the longest CTI, $F(1, 34) = 9.95$, $MSE = 1170.58$. Its average size was 23 ms. The only additional significant source of variation was the interaction of Number-of-Tasks and CTI, $F(6, 102) = 3.80$, $MSE = 7786.74$, but this effect was not significant when the partial set of trials was analyzed, $F = 1.65$. A similar finding was observed by Biederman (1973) but in the present case at least it might be attributed to the confounding of Number-of-Tasks and the amount of practice on each task (Fig. 5).

Although the interaction of CTI, Task-Switch, and Number-of-Tasks was insignificant, inspection of the results suggests that, in the very short Cue-Target-Interval, task-switching cost was smaller in the two-task condition than in the three-task condition and the four-task condition. Furthermore, this pattern was similar in the two experiments. A planned contrast indicated that the trend was marginally significant, $F(1, 36) = 4.06$, $p = .051$, $MSE = 5563.24$, while the interaction of this contrast with Experiment was nonsignificant, $F < .4$.

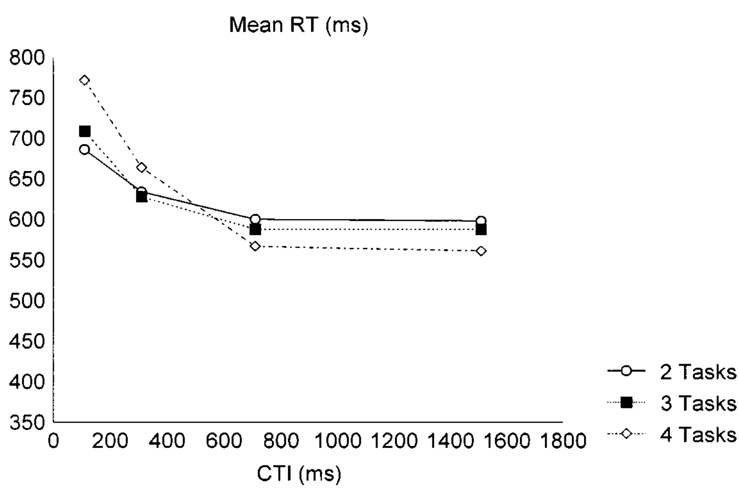

FIG. 5. Mean RT (in milliseconds) as a function of Cue-Target-Interval (CTI) and Number-of-Tasks in Experiments 3a and 3b.

Errors. A similar ANOVA was conducted on the mean error rates. Task-Switch was the only significant source of variation, $F(1, 34) = 4.79$, $MSE = .000375$, with a slightly higher error rate in the switch condition (2.2%) than in the no-switch condition (1.7%). The same effect only approached significance in the partial set, $p = .055$.

Discussion

The principal goal of the present Experiment was to estimate the duration of task preparation and the size of residual switching cost in the present paradigm. It is therefore important that both components were in fact obtained: switching cost was drastically reduced (the preparatory component) but not eliminated (the residual component) by preparation.

We suggested two estimates of task preparation time. The first estimate is preparatory cost (Fagot, 1994; Meiran et al., 2000), and its size was 141 ms. The second estimate is based on the function relating switching cost to CTI (Fig. 6). Visual inspection of the results indicate that lengthening CTI produced substantial reductions of switching costs up to the CTI of 710 ms, but not any further. Accordingly, preparing for a switch can be estimated to take about 700 ms or, more conservatively, at least between 110 ms (310–200 ms, 200 ms reflecting purely perceptual analysis; see Moulden et al., 1998) and 510 ms (710–200 ms).

With these two estimates in mind, we can return to our principal question. It is clear that the effect of task switching on readiness time was an order of magnitude smaller than the objectively estimated preparation time. These results seem to rule out the possibility that the effect of task switching on readiness time resulted only from true differences in task preparation time.

Our second goal was to validate our interpretation of RT switching cost in Experiments 1 and 2. The results support this interpretation since residual switching cost

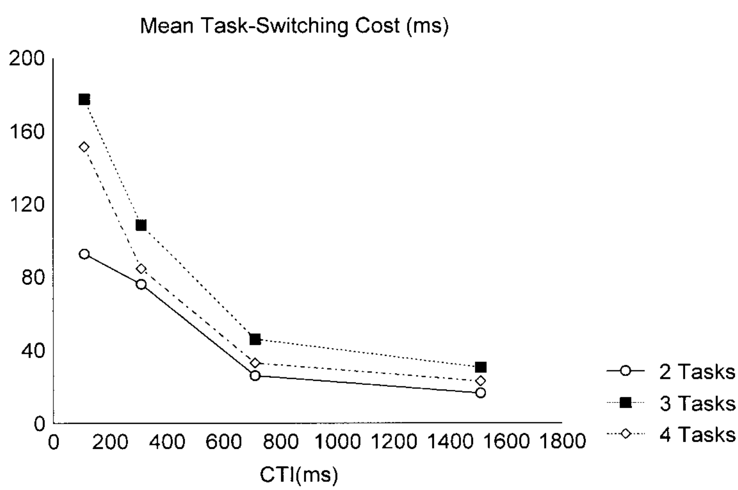

FIG. 6. Mean Task-Switching Cost (Switch RT minus No-Switch RT in milliseconds) as a function of Cue-Target-Interval (CTI) and Number-of-Tasks, in Experiments 3a and 3b.

was 23 ms, on average, a value similar to the RT switching cost of 14 and 26 ms observed in Experiments 1 and 2, respectively. Thus, the present results suggest that although readiness time is sensitive to task switching, participants are unlikely to be aware of the progress or the completion of their preparation for a switch. A viable interpretation is that the effect of task-switch on readiness time reflects a guessing strategy based on the fact that participants estimate that preparation be more difficult in the switch condition.

GENERAL DISCUSSION

The goal of the present experiments was to examine whether participants are consciously aware of the progress or completion of their cognitive processes involved in preparing for a task switch. This process is commonly considered a classic example of cognitive control, as currently studied in cognitive experimental psychology. Our results strongly suggest poor conscious awareness of task readiness. This was mainly seen in (1) longer readiness times being associated with longer RTs; (2) in the fact when participants were asked to indicate readiness prematurely, this resulted in a shift in speed emphasis rather than in readiness; and (3) in that the effect of task switch on readiness time was in an order of magnitude smaller than our estimates of objective preparation time.

It is interesting to note that only recently we became aware of results by Gopher, Armony, and Greenshpan (2000). These authors measured readiness times in a task-switching paradigm, which differed from the present paradigm in an important respect. Specifically, the instructional cue, and hence readiness responses, did not come immediately before the target stimulus. As would be predicted from the present account, it was found that readiness responses increased with increasing perceived difficulty. Critically, preparation times were unrelated to basic task performance and were sometimes positively related, sometimes negatively related, and sometimes unrelated to switching cost. Their results support our suggestion that readiness responses do not represent actual readiness. Given the fact that target responses did not follow readiness responses, speed–accuracy trade-off did not spill from one to the other, hence the lack of relation between the measures instead of the positive relation that we had observed.

Given that for many authors the relation between control processes and consciousness is apparently self-evident, these results are puzzling and require at least some fine-tuning of our understanding of cognitive control. So, if one would like to maintain the idea of conscious control of voluntary action (which is not really necessary to account for our findings), how could this be done?

A first possibility is to object that the preparation for a task switch, or even more narrowly, the preparation for the task switch as instantiated in the present paradigm, constitutes an exception to the rule. Of course, given the widespread assumption that task switching is a prime example of control processes at work (e.g., Monsell, 1996), this argument would be far-fetched. Moreover, for such an argument to be taken seriously, one should be able to come up with some reasonable explanation of why the presently studied process is an exception.

A second, also somewhat weak argument might go like this. If we assume, like

Shallice (1994), that control is organized hierarchically and further assume that conscious awareness is involved only in operations at the top of the hierarchy (e.g., Kleinsorge & Heuer, 1999; Zelazo & Frye, 1996), one might explain the present results by arguing that the control processes involved in task switching *do not* belong to, or reside at, the top of the hierarchy. By applying the current line of reasoning participants need not be consciously aware of preparing for a task switch, only of the high-order rule of switching.

A third possibility is to assume that conscious awareness is only required to launch control operations but not to monitor their progress. The reasoning is that, when control operations are being launched, a choice between alternative routes of action is required, and choice is among the conditions presumably requiring conscious control (e.g., Norman & Shallice, 1986). Recent results by Gotler, Meiran, and Tzelgov (submitted) challenge this approach by showing strong unconscious influences in the launching phase of task preparation.

A fourth, somewhat related possibility is to assume that participants need only be aware of their goals (e.g., Ach, 1905; Baars, 1987; James, 1890; Lotze, 1852). Once a (conscious) goal is selected and activated (e.g., transferred to some ''working memory''), it more or less automatically (and unconsciously) activates and organizes the relevant action components, that is, takes over cognitive control. For example, Prinz (1997; cf. Hommel, in press) had pointed out that the classic treatment of stimuli as invoking responses must be inaccurate. The reason is that the responses being studied in cognitive experiments would have never been emitted without the intention to act. In other words, one could think of intentions as activated goals which, together with the (the representation of the) stimulus, activate and organize the response (cf., Bargh & Chartrand, 1999; Gollwitzer, 1999). Along a similar line, Meiran (2000a; 2000b) presented a detailed model of task-switching performance. A crucial assumption in that model is that participants maintain all stimulus–response mappings simultaneously active. According to the model, task-appropriate responses are ensured by a relatively simple strategy of selectively attending to the relevant stimulus dimension, without what may be called ''a goal change.''

In any case, it seems clear that the present results have important implications for the use of subjective measures of cognitive control and preparation. Until now, it was commonly accepted that subjective reports should be treated with extreme caution (e.g., Nisbett & Wilson, 1977); yet, this tenet referred only to task execution processes. This left the possibility that, given the presumed tight relation between cognitive control and conscious awareness, subjective reports are still valid when studying cognitive control. Unfortunately, though, the present results suggest that subjective reports concerning control processes may be invalid as well.

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