Exploring task-set reconfiguration with random task sequences

Emilio G. Milán, Daniel Sanabria, Francisco Tornay, & Antonio González

Departamento de Psicología Experimental, Universidad de Granada, Spain

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CORRESPONDENCE TO: Emilio G. Milán, Departamento de Psicología Experimental, Universidad de Granada, Campus Cartuja s/n, 18071, Granada, Spain.

E-MAIL: egomez@ugr.es

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ABSTRACT

The task-switch paradigm has helped psychologists to gain insight into the processes involved in changing from one activity to another, new activity. However, the literature has yielded discrepant results regarding to task-set reconfiguration. We report two experiments investigating the reconfiguration process elicited by task switching. We claim that the controversy is partly due to the confusion of two different experimental conditions: predictable task switching and random task switching, which may involve different processes. The results of the present study demonstrate that, whereas the results in predictable switching conditions are compatible with an exogenous-reconfiguration hypothesis, random task switching produces a more gradual, decay-like switch cost reduction with task repetition.

1. Introduction

It has been suggested that in order to behave coherently, people have to set up and link together a number of component processes that connect sensory analyses with motor responses, giving rise to a particular *task-set* (e.g., Monsell, 1996). We are constantly switching from one activity to another, requiring reconfiguration of task-set in order to achieve the goals of the upcoming task. A number of studies have shown that the activation of this process (or processes) of task-set reconfiguration normally leads to an impairment in performance, typically measured as a decrease in accuracy and an increase in reaction time (RT; e.g., Allport, Styles, & Hsieh, 1994; Allport & Wylie, 1999; Gilbert & Shallice, 2002; González, Milán, Pereda, & Tornay, submitted; Meiran, 1996; Meiran, Chorev, & Sapir, 2000; Milán, González, Pereda, & Tornay, in press; Milán, González, Tornay, & Sanabria, submitted; Rogers & Monsell, 1995; Spector & Biederman, 1976; Tornay & Milán, 2001; see Jersild, 1927, for an early study of task-set reconfiguration).

In a typical study of task-set reconfiguration, participants alternate between two behavioral tasks (i.e., task switching). For instance, participants have to indicate the spatial position of a stimulus on trial N, its color on trial N+1, its position again on trial N+2, and so on. If participants' performance in this condition is compared with that in a baseline condition in which they carry out a single task (e.g., indicate the position of the stimulus on every trial), the results usually show an increase in RT or a decrease in accuracy. This effect has been termed the *switch cost* (e.g., Roger & Monsell, 1995). According to the task switching literature, this switch cost is the behavioral manifestation of the extra processes involved in reconfiguring the task-set needed in order to perform the new task.

In their seminal study, Roger and Monsell (1995) reported a series of experiments in which they investigated the nature of the processes involved in task switching. They showed that although part of the switch cost could be eliminated by increasing the preparation time for the upcoming task, it never disappeared entirely before the first repetition trial of the new task. In light of their results, the authors suggested that there are two different components of switch costs: One component that can be eliminated by an active endogenous control process and another that is only eliminated by the presence of the target in the new task (i.e., a residual switch cost). However, although the results of subsequent investigations appear to agree with Roger and Monsell's conclusions (e.g. Dreisbach, Haider, Kawski, Kluwe, & Luna, 1998; Gilbert & Shallice, 2002; Gopher, Armony, & Greenspan, 1998; Milán et al., in press; Ruthruff, Remington, & Johnston, 2001; Sohn & Anderson, 2001), others have shown that switch costs can be completely eliminated if enough time is allowed to prepare for the upcoming task (e.g., Meiran, 1996; Meiran et al., 2000; Tornay & Milán, 2001).

In a recent study, Tornay and Milán (2001) conducted a series of experiments that shed light on the apparently contradictory results emerging from the previous task switching literature. They compared participants' performance between two conditions; one in which tasks switched predictably, and another where the tasks switched randomly. They studied how the RT varied with the number of repetitions of the same task. Crucially, while in the predictable switch condition the switch cost never disappeared before the onset of the target in the new task (cf. Rogers & Monsell, 1995), the switch cost was completely eliminated in the random switch condition if enough time was allowed between the cue that signalled the next task and the target (cf. Meiran, 1996). Interestingly, these results appear to demonstrate that part of the controversy emerging from previous studies was due to a methodological shortcoming regarding the predictability of the upcoming task. It is worth noting that while task switching was predictable in Rogers and Monsell's study, the tasks alternated at random in Meiran's investigation.

Tornay and Milán (2001) interpreted the difference between random and predictable switch conditions by noting that in the random switch condition there was more uncertainty than in the predictable switch condition, during the interval between the response to one task and the cue that signalled the new task. Such uncertainty has been shown to activate the anterior cingulate cortex and the prefrontal cortex, which have been associated with attentional or control mechanisms (e.g., Eslinger & Grattan, 1993; Pardo, Pardo, Janer & Raichle, 1996; Sohn, Ursu, Anderson, Stenger, & Carter, 2000). Therefore, it might be possible that the random switch condition in Tornay and Milán's investigation (see also Meiran, 1996) elicited a more attentional or controlled processing than the predictable switch condition. In the predictable switch condition, the onset (or response to) the target appeared to be sufficient to complete the reconfiguration of the task-set, as the switch cost was entirely eliminated after the first repetition of the new task. According to this result the authors suggested that there was a larger involvement of exogenous processing in the predictable switch condition than in the random switch condition.

However, Tornay and Milán (2001) noted that the endogenous process of reconfiguration may have eliminated the switch cost in the random switch condition in their study, making it impossible to detect any additional decrease in reaction time due to exogenous reconfiguration (i.e., that elicited by the presence of the target stimuli in the new task). Tornay and Milán's results are therefore not conclusive, since the authors found almost no switch cost in the random switching condition. It might be possible that predictable and random switching would show a similar pattern of reconfiguration of the task-set in conditions with a larger switch cost in the random switch condition.

In the present study, we used a short stimulus onset asynchrony (SOA; the time between the cue that signals the next task and the target) in order to overcome this possible methodological shortcoming; that is, that it may be impossible to detect any effect of task repetition on the pattern of reconfiguration within the random switch condition when a long SOA is used. The novel question addressed here was whether the pattern of reduction of the switch cost across the number of repetitions of the same task would be different depending on the predictability of the task when a short SOA was used. In the predictable switch condition, we predicted that the switch cost would dissipate after the first repetition of the same task, indicating the importance of the appearance of the stimuli for complete reconfiguration of the task-set (cf. Rogers & Monsell, 1995). By contrast, in the random switch condition, we expected a progressive reduction in RT with number of repetitions of the same task (cf. Tornay & Milán, 2001).

2. Experiment 1

2.1. Methods

2.1.1. Participants. Eighteen undergraduate students (12 female, 6 male) from the University of Granada took part in Experiment 1. They were given course credit in exchange of their participation. All the participants reported normal or corrected-to-normal vision.

2.1.2. Design. We used a repeated-measures design with three independent variables, two of which were varied trial-by-trial: Task (number vs. letter), and Number of repetitions, which had three levels: 0 repetition (trials in which the task was different from that on the previous trial), 1 repetition (trials in which the task was the same as that on the previous trial) and 2 repetition (trials in which the task was the same as that on the two previous trials). The third variable was Predictability: In one session, tasks switched at random and in the other the switch between tasks was predictable.

2.1.3. Apparatus and stimuli. The stimuli were presented on a computer screen controlled by a PC (Pentium III) that was also used to collect participants' responses. We used the MEL program (Schneider, 1988) to generate and control stimulus presentation. Participants sat in a comfortable chair, in a dimly-illuminated room while taking part in the experiment.

On every trial, either a plus sign (+) or an asterisk (*) appeared on the centre of the screen indicating the task that the participants had to perform, and acting as a fixation point. The plus sign (+) signalled the number task and the asterisk (*) indicated the letter task. Both signs subtended 1.5º x 1.5º of visual angle. Later on in the trial, a stimulus pair (2.8º x 1.5º degrees of visual angle), consisting of a letter and a number (e.g., A7, 5A, 2B,), was presented on the centre of the screen, replacing the fixation point (i.e., cue). We manipulated the interval between the cue and the stimulus pair, as explained below. The stimulus pair remained on the screen for 500ms.

2.1.4. Procedure. Participants were asked to perform one of two possible tasks. They had to indicate either whether the number was odd or even (number task) or whether the letter was a vowel or a consonant (letter task). In both tasks the participants responded by pressing either the "b" or the "n" keys on the keyboard. This way, both tasks shared the same stimuli and responses. Half of the participants had to press "b" when the number was even or the letter was a vowel and "n" when the number was odd or the letter was a consonant. The reverse stimulus-key mapping was used for the remaining participants. Each participant was randomly assigned to either mapping. Thus both tasks shared the same stimuli and responses. The participants were given a maximum of 2500 ms after the appearance of the stimulus pair to respond before proceeding to the next trial. The response-stimulus-interval (RSI) was 300 ms, resulting from adding together the 100 ms ITI (the time interval between the participant's response and the onset of the next cue), and the 200 ms SOA.

In the predictable switch condition, tasks alternated every 3 trials (e.g., LLL-

NNN), and in the random switch condition tasks switched at random (e.g., LNLLNN). The participants completed 700 trials distributed across two experimental sessions. In one session, task-switch was predictable, and in the other session tasks switched at random. The order of the two sessions was counterbalanced across participants. The participants completed 5 blocks of 70 trials in each switch condition, separated by a short rest. Prior to the experimental session, participants completed a practice block of 70 trials in order to familiarize them with the task. The data from this block was not considered in the analysis. On each block, all possible combinations of stimuli (even-vowel, e.g., 4A; even-consonant, e.g., 4B; odd-vowel, e.g., 5A; odd consonant, e.g., 5B), in the two possible orderings (number-letter and letter-number) were presented. Participants were instructed to respond as quickly as possible while trying to avoid errors.

2.2. Results and Discussion

The RT (for correct responses only) and the accuracy data were submitted to a three-way repeated-measures analysis of variance (ANOVA) with the factors Predictability (random vs. predictable), Task (number vs. letter), and Number of repetitions (0, 1, and 2). The analysis of the RT data revealed a significant main effect of Number of repetitions, $F(2,34) = 16.32$, $MSE = 4175.88$, $p<.001$. Crucially, there was a significant interaction between Predictability and Number of repetitions, $F(2, 34) = 7.96$, $MSE = 2025.37$, $p<.01$ (see Figure 1). Subsequent post-hoc analyses (Tukey HSD) revealed that the switch cost (i.e., the difference in RT between 0 and 1 repetition trials) was not significant in the random-switch condition, $p=.71$. However, the difference between 0 and 2 repetition trials, $p<.001$, and between 1 and 2 repetitions trials, $p<.001$, were statistically reliable. The predictable switch condition showed a significant switch cost, $p<.001$, but the difference in RT between 1 and 2 repetition trials was not reliable, *p*=.99. The analysis of the RT data also revealed a significant main effect of Task, $F(1, 17) = 30.77$, $MSE = 7895{,}74$, $p<.001$, with participants responding more rapidly to the number task than to the letter task overall (775 vs. 842 ms, respectively). There was also a significant interaction between Number of repetitions and Task, $F(2,34) = 21.30$, $MSE = 2093.21$, $p<.001$ (see Table 1). Post-hoc tests (Tukey HSD) revealed a significant switch cost in the number task, $p<.001$, but not in the letter task, p=.57. However, the difference between 1 and 2 repetition trials was significant in the letter task, $p<.001$, but not in the number task, $p=.73$.

None of the terms of the ANOVA performed with the accuracy data reached significance.

Insert Figure 1 and Table 1 about here

The main conclusion to draw from Experiment 1 is that a different pattern of switch cost reduction was found depending on the predictability of the task. The results from the predictable switch condition showed a reliable reduction in RT between 0 and 1 repetition trials, and a lack of any further reduction between 1 and 2 repetition trials. Note that this result replicates previous findings reported in the literature (e.g., González et al., 2002; Rogers & Monsell, 1995; Tornay & Milán, 2001). However, the random switch condition led to a different pattern of results. Namely, there was a progressive decrease in RT as the number of repetitions of the same task increased. Therefore, we argue that the results of Experiment 1 confirm Tornay and Milán's suggestion that task-set reconfiguration depends upon the predictability of the task. Note that while the pattern of results in the predictable switch condition appears to agree with Rogers and Monsell's exogenous account of task-set reconfiguration, the results from the random switch condition suggest the need for another explanation.

However, although a significant reduction in RT between the 1 and 2 repetition trials was found in the random switch condition, we found no significant switch cost, typically considered as the difference between 0 and 1 repetition trials. Therefore, one might argue that the switch cost in the random switch condition was displaced compared to the predictable switch condition, instead of showing a progressive reduction with the number of repetitions. We conducted Experiment 2 in order to address this issue.

3. Experiment 2

In Experiment 2, we manipulated the length of the sequence of repetitions of the same task in the random switch condition in order to investigate the pattern of decay of the RT. Note that the only way to completely determine the shape of a function is to use a very large number of points (i.e., number of repetitions of the same task). If we were attempting to manipulate the predictable switch condition, we would simply have run a series of blocks differing only in the number of task repetitions (e.g., blocks with LLNN sequences, blocks with LLLNNN sequences, and blocks with LLLLNNNN sequences). However, such an approach was very difficult to implement in the present case, given that the task switch had to occur at random. Instead, we incremented the number of points in a series of stages, in order to obtain successive, more detailed estimates of the function. To do this, we varied the length of the switch sequences across blocks, as will be explained in the Procedure section (see below). We then obtained data for sequences consisting of only two task repetitions of the same task, for sequences consisting of three repetitions of the same task, and for sequences of four repetitions of the same task. Different sequence lengths of task repetitions were run within the same block of trials to produce a random sequence, but their frequency was manipulated between blocks.

3.1. Methods

3.1.1. Participants. Twelve undergraduates (10 female and 2 male) from the University of Granada took part in Experiment 2. None of them had participated in Experiment 1. All reported normal or corrected-to-normal vision.

3.1.2. Design. We used the same design as in the previous experiment, except for the following: The tasks always switched at random, and we manipulated the length of the switch sequence as will be explained below.

3.1.3. Procedure. The procedure was identical to that in Experiment 1, except for the following. There were 1800 trials divided into two experimental sessions. Each session had three blocks, in which we manipulated the frequency of three different sequences of repetitions of the same task (see below). The blocks were counterbalanced across participants. After each block, participants were allowed to have a short break. After the first session, participants rested for 15 minutes. All participants conducted the two sessions.

In each block, one particular sequence of task repetitions was most probable, whereas other sequences were less probable. This factor is called Sequence length, and has three levels. In the first level of Sequence length (S2; i.e., 2 repetitions of the same task), the sequence with 1 repetition trial (producing two-trial sequences, LL or NN) occurred with a probability of 70%. The remaining 30% of the sequences were equally divided between those with 2 and 3 repetition trials. In the second level of Sequence length (S3), the sequences with 2 repetition trials (three-trial sequences) had a 70% probability of occurring. The sequences with 1 and 3 repetition trials were equally divided over the other 30% of the trials. Finally, in the third level of Sequence length (S4), the sequences with 3 repetition trials (four-trial sequences) appeared with a probability of 70%. The other 30% of sequences were equally divided between those with 1 and 2 repetition trials.

3.2. Results and Discussion

The RT (for correct responses) and accuracy data were submitted to three-way ANOVA with the factors Sequence length (S2, S3, and S4), Task (number vs. letter), and Number of repetitions (0, 1, 2, and 3).

3.2.1. RT

The analysis of the RT data showed a significant main effect of Sequence length, $F(2, 22) = 4.60$, $MSE = 20481,87$, $p<.05$. Post-hoc analyses (Tukey HSD) revealed that participants responded more rapidly on the S4 condition than on both the S2 condition, $p<.05$, and on the S3 condition, $p<.05$. Crucially, the analysis also revealed a significant main effect of Number of repetition, $F(3,33) = 13.21$, $MSE = 8131.56$, $p<.001$ (see Figure 2). This effect was due to significantly faster RTs being reported on 2 and 3 repetition trials than on 0 repetition trials, and on 3 than on 1 repetition trials, all *ps*<.05 (Tukey HSD). The interaction between Number of repetitions and Task also reached significance, $F(3,33) = 10.07$, $MSE = 2261.54$, $p<.001$ (see Figure 3). In the number task, subsequent post-hoc analyses (Tukey HSD tests) revealed significant differences between 0 and 1 repetitions trials (i.e., a switch cost was observed), $p<.05$, between 0 and 2 repetition trials, $p<.01$, and between 0 and 3 repetition trials, $p<.001$. The letter task showed that the switch cost was not significant, p=.52 (Tukey HSD). However, the participants responded more rapidly on 3 repetition trials than on 0 repetition trials, $p<.001$, on 2 repetition trials than on 1 repetition trials, $p<.05$, on 3 repetition trials than on 1 repetition trials, $p<.001$, and on 3 repetition trials than on 2 repetition trials, $p<.05$.

Insert Figures 2 and 3 about here

3.2.2. Accuracy

ANOVA revealed a significant interaction between Sequence length, Task, and Number of repetitions, $F(6,66) = 5.05$, $MSE = 9.14$, $p<.001$, and so we analysed the accuracy data for each level of the Sequence length factor separately. In the S2 condition, there was a significant interaction between Task and Number of repetitions, $F(3,33) = 3.31$, $MSE = 9.41$, $p<.05$ (see Table 2). There was also a significant main effect of Number of repetitions, $F(3,33) = 4.70$, $MSE = 46.13$, $p<.01$. Tukey HDS post-hoc analyses revealed that participant responded more accurately on 3 repetitions trials than on 0 repetitions trials, and on 3 repetitions trials than on 1 repetition trials. The interaction between Task and Number of repetitions was also significant in the S3 condition, $F(3,33) = 4.27$, $MSE = 24.70$, $p<.05$ (see Table 2). In the S4 condition there was a significant main effect of the Number of repetitions, $F(3,33) = 7.09$, $MSE = 22.35$, $p<.001$. Subsequent post-hoc tests (Tukey HSD) revealed that the participants responded more accurately on the 3 repetition trials than on the 0 repetition trials, $p<.01$, and on 3 repetition trials than on 1 repetition trials, $p<.01$.

Insert Table 2 about here

The results of Experiment 2 confirmed the pattern of results obtained in the random switch condition of Experiment 1. Namely, a progressive reduction of RT (and errors) with the number of repetitions of the same task. Therefore, the outcome of Experiment 2 appears to rule out an account of the results of the random switch condition in Experiment 1 based on a displacement of the switch cost to the 1 repetition trials. Furthermore, the results of Experiment 2 demonstrate, once again, the importance of studying the general pattern of switch cost reduction, rather than simple differences between 0 repetition trials and 1 repetition trials.

4. General Discussion

The most important result to emerge from the present study is that the pattern of task-set reconfiguration depends upon the predictability of the task. Experiment 1 showed that the switch cost was completely eliminated after the first repetition trial in the predictable switch condition, replicating several previous findings (e.g., Rogers & Monsell, 1995; Tornay & Milán, 2001). However, the random switch condition produced a more gradual reduction of the switch cost as compared to the repetitions of the same task. Experiment 2 confirmed the results of Experiment 1 in the random switch condition, showing a progressive reduction of RT and errors across repetitions of the same task.

The results of the present study appear to suggest that the reason for the apparent inconsistency between previous research in task switching (i.e., the different patterns of reconfiguration of the task-set across different studies) might be attributable to a methodological feature of the experimental designs used, rather than to a theoretical or empirical basis. By comparing the two main experimental task-switching procedures found in the literature (i.e., random and predictable task switching), in the current study we were able to demonstrate that a different pattern of task-set reconfiguration is involved depending on the predictability of the upcoming task. Furthermore, as suggested by Tornay and Milán (2001), it is very likely that different mechanisms are implicated depending on the predictability of the switch between tasks. While the results of the predictable switch condition in Experiment 1 appear to agree with an exogenous account of the process of task-set reconfiguration (e.g., Rogers & Monsell, 1995), the result in the random switch condition in Experiments 1 and 2 leads to a different conclusion.

Our results suggest that the process of reconfiguration of task-set in the random switch condition can be considered as passive, but not entirely exogenous, as it seems less dependent on target-stimulus processing than the process of reconfiguration involved in the predictable switch condition. In contrast to the predictable switch condition, the onset of the cue (indicating the next task) did not complete the reconfiguration of the task-set. It is worth noting that this result is consistent with Tornay and Milán's (Tornay & Milán, 2001; Experiment 3) previous findings. Although only marginally significant, the authors reported a reduction of the RT with the increasing of the number of repetitions of the same task in the random switch condition. However, it is reasonable to wonder whether shortening the SOA in the present study might have produced some confounds. Perhaps the process of interpreting the cue and preparing for the next task in the random switch condition could not be completed prior to stimulus onset. To address this issue, it should be noted that if the process was not completed, it would have affected the mean RT and accuracy, but not the general pattern of a reduction in the switch cost. Moreover, the non- significant difference in accuracy between the random switch condition and the predictable switch condition in Experiment 1, and the progressive reduction of the RT across the number of repetitions in Experiment 2, do not support an account of the results based on a failure of the interpretation of the cue and the preparation for the oncoming task.

Another interesting result to emerge from the present study regards the different pattern of RT reduction across the number of repetitions as a function of the task. Both Experiment 1 and 2 showed significant interactions between Task and Number of repetitions, with significant switch cost (considered as the difference between 0 and 1 repetition trials) in the number task but not in the letter task overall. However, when examining the RT across the number of repetitions in the letter task, decreases in RT between the 1 repetition trials and 2 or 3 repetitions trials were reported (both in Experiment 1 and 2). Note that a simple analysis of the difference in RT between the 0 and 1 repetition trials would have suggested that switching from the number task did not impair participants' performance in a subsequent trial in the letter task, given the non-significant difference in RT found between the 0 and 1 repetition trials in this condition. However, the present results demonstrate that switching from the number task did impair performance in a subsequent trial in the letter task, again highlighting the need to investigate performance across the number of repetitions of the same task.

Note that a comparison between the patterns of task-set reconfiguration reported in the number task with that in the letter task would suggest that different processes might be involved depending on the task that people perform (or will perform). However, an alternative account is that the same processes are involved, but that their behavioral manifestation is different depending on the task. This issue falls outside the scope of the present study, and further research is needed in order to clarify and explain the difference between tasks, regarding the pattern of task-set reconfiguration, reported in the present investigation.

It is also interesting to note that increasing the frequency of a given sequence length in Experiment 2 might have increased the predictability of the task (e.g., S3 condition). This could have made the random switch condition more similar to the predictable switch condition. It might therefore be possible that the progressive reduction in RT with the number of repetitions in the random switch condition somehow reflects an interaction between endogenous and exogenous reconfiguration processes. However, at this stage we cannot make strong claims about the nature of such processes. In future studies, it will be interesting to combine behavioral paradigms, such as the one used here, with neuroimaging techniques to provide further explanations of the processes underlying the reconfiguration of task-set in the random switch condition.

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FIGURE LEGENDS

Figure 1. Mean RT in responding to the target stimuli in Experiment 1, as a function of the Predictability and the Number of repetitions factors.

Figure 2. Mean RT in responding to the target stimuli in Experiment 2, as a function of the Number of repetitions factor.

Figure 3. Mean RT in responding to the target stimuli in Experiment 2, as a function of the Task and the Number of repetitions factors.

Table 1. Mean RT (ms) responding to the target stimuli in Experiment 1, as a function of the Task and Number of repetitions factors.

Repetitions	Number	Letter
0	825	855
1	745	868
2	754	802

Table 2. Mean percentage of errors in responding to the target stimuli in Experiment 2, as a function of Sequence length, Task, and Number of repetitions.

	Sequence length					
	S2		S3		S4	
Repetitions	Number	Letter	Number	Letter	Number	Letter
0	15	13	14	14	15	11
1	13	16	14	16	14	13
2	13	11	14	10	12	10
3	10	10	18	10	8	8

Figure 1.

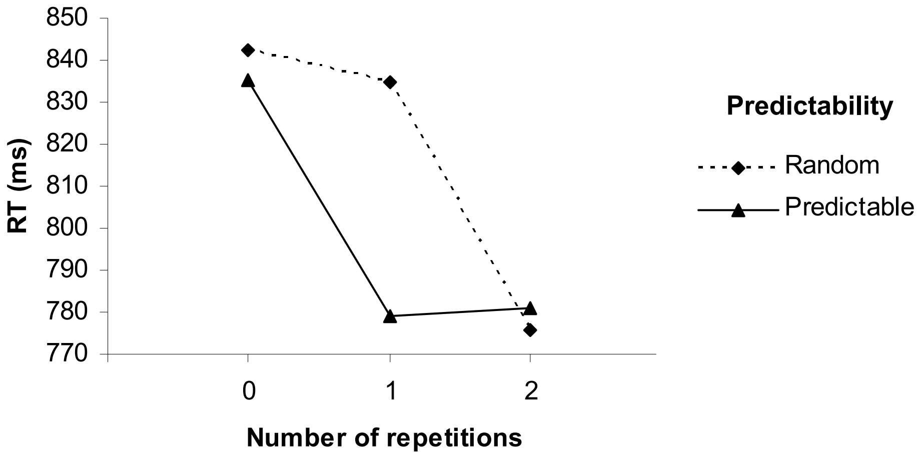

850
840
830
820
810
800
790
780
770
RT (ms)
0
1
2
Number of repetitions
Predictability
Random
Predictable

Figure 2.

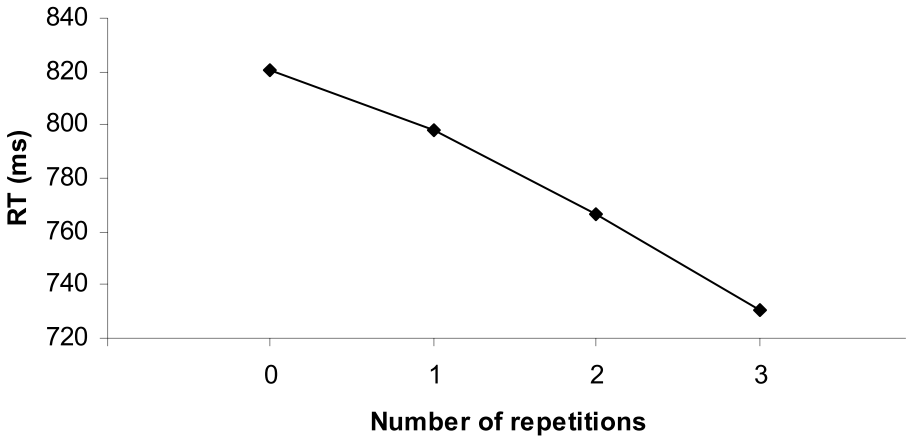
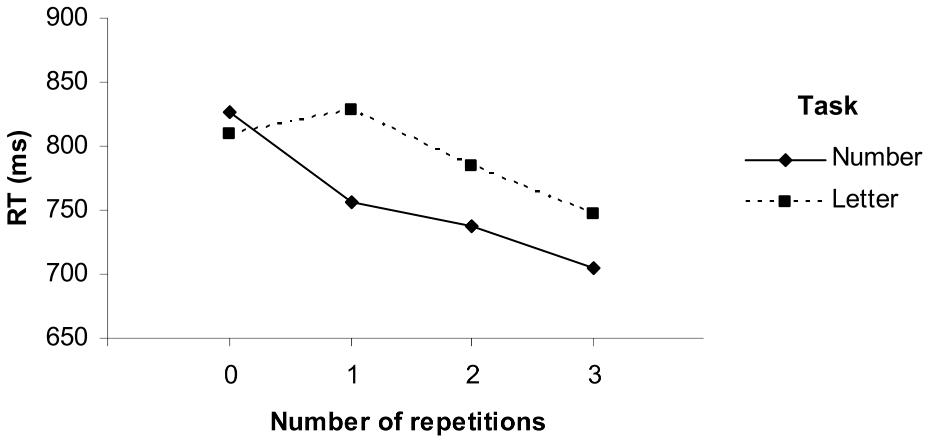


Figure 3.


900
850
800
750
700
650
RT (ms)
0
1
2
3
Number of repetitions
Task
Number
Letter