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ORIGINAL ARTICLE

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# Modeling cognitive control in task-switching

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**Abstract** This article describes a quantitative model, which suggests what the underlying mechanisms of cognitive control in a particular task-switching paradigm are, with relevance to task-switching performance in general. It is suggested that participants dynamically control response accuracy by selective attention, in the particular paradigm being used, by controlling stimulus representation. They are less efficient in dynamically controlling response representation. The model fits reasonably well the pattern of reaction time results concerning task switching, congruency, cue-target interval and response-repetition in a mixed task condition, as well as the differences between mixed task and pure task conditions.

## Introduction

Perhaps one of the best indicators of cognitive control is the fact that the same stimuli invoke different actions in different situations. This observation indicates that actions are not controlled exclusively by environmental stimuli. For example, when presented with a word, a participant might read it, press a key indicating it is a word, press a key indicating that they have seen it before, say the number of syllables, etc. Participants have the flexibility to control their responses by taking situational constraints, such as task demands, into account. The present article is concerned with processes, which enable this control. It does so by offering an explicit quantitative model of performance in the task switching paradigm (e.g., Allport et al., 1994; de Jong, 1995, in press; Fagot, 1994; Jersild, 1927; Meiran, 1996; Rogers & Monsell, 1995; Rubinstein, Mayer & Evans, in press; and D. Gopher, L. Armony & Y. Greenshpan, Switching tasks and attention policies and the ability to prepare for such shifts, submitted).

I have used the following paradigm to study task switching behavior (Fig. 1, e.g., Meiran, 1996). The participants were required to indicate the location of a target stimulus (smiling face) within a 2 × 2 grid. Two tasks were ordered randomly. One task involved "up" versus "down" discrimination (ignoring the horizontal dimension), while the other task involved "right" versus "left" discrimination (ignoring the vertical dimension). Prior to the presentation of the target stimulus, the participants were instructed, by means of symbolic cues, which task to perform. Note that in this paradigm, like in most task-switching paradigms, the target stimuli as well as the responses are bivalent, that is, relevant for both tasks. Specifically, a given target stimulus could be classified both in up-down terms and in right-left terms. Similarly, a given physical response could serve to indicate a nominal response to either task, e.g., up, belonging to the up-down task, and left, belonging to the right-left task.

Four independent variables were examined. The first variable, Task-Switch, was defined in relation to the preceding trial; that is, the "switch" condition occurred when the preceding trial involved a different task than the task in the current trial, while the "no-switch" condition was when the task was the same as in the previous trial. The second variable, "Response-Repetition", was also defined in relation to the preceding trial. That is, a response-repetition occurred when the physical response was repeated from the preceding trial, while response changes occurred when the physical response in the preceding trial and the physical response in the current trial were different. To induce preparedness, we manipulated the Cue-Target Interval (CTI), which is the third independent variable. Specifically, if the CTI was long this made it possible to prepare for the task switch, while it was assumed that there was little or no preparation when the CTI was short. Finally, Congruency, the fourth independent variable, referred to whether the

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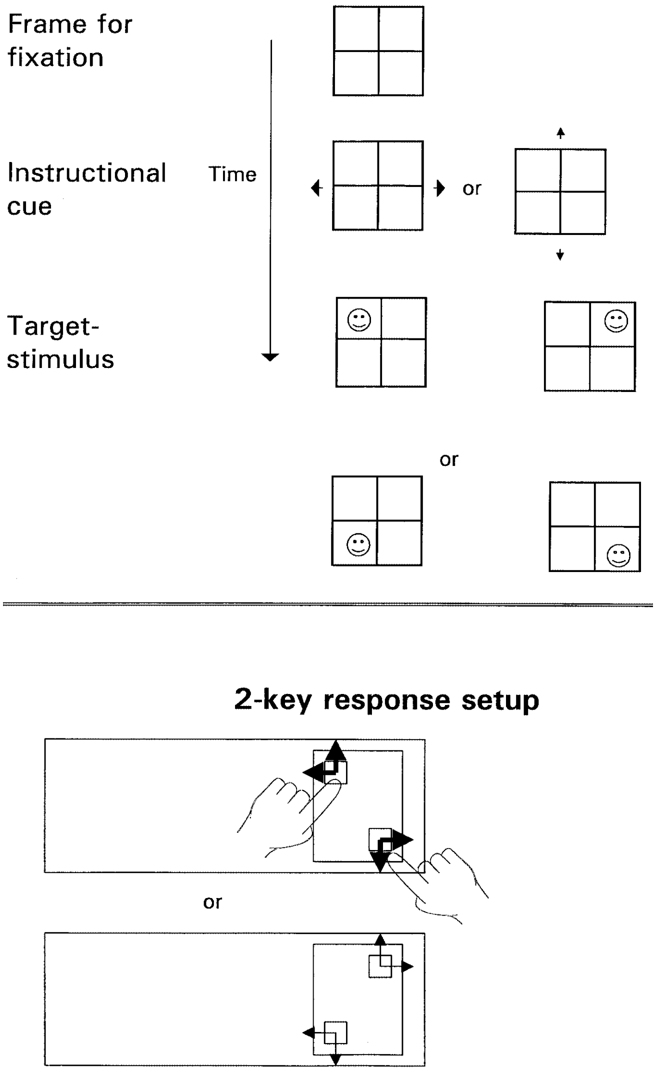

**Fig. 1** The experimental paradigm

same physical response would have been regarded correct in both tasks. For example, when the target was located in the upper-left position, the correct response was pressing the upper-left key, regardless which task was involved (congruent condition). In contrast, when the target was in the upper-right location, the two tasks called for different responses (incongruent condition).

The model delineated below describes performance under "standard" conditions, when the target stimuli and the responses are bivalent, i.e., relevant for both tasks. Nonetheless, it makes clear predictions regarding univalent stimuli and responses. Returning to the standard conditions, the results indicate a "task switching cost" [switch reaction time (RT) > no-switch RT], i.e., a main effect for Task-Switch. In addition, Task-Switch is involved in significant interactions. First, studies have shown that preparation reduces switching costs, i.e., Task-Switch interacts with CTI (or an analogous variable, representing preparation time; e.g., Allport et al., 1994; Fagot, 1994; Goschke, in press; Hartley et al., 1990; Meiran, 1996, in press; Rogers & Monsell, 1995). Second, although preparation reduces switching cost, it does not eliminate it (de Jong, in press; Fagot, 1994; Goschke, in press; Meiran, 1996; Rogers & Monsell, 1995). Third, Congruency (or an analogous variable) has been frequently shown to have a significant main effect (congruent RT < incongruent RT; e.g., Fagot, 1994; Meiran, 1996; Rogers & Monsell, 1995; Monsell et al., 1998; Sudevan & Taylor, 1987; and D. Gopher et al., submitted). Fourth, a small two-way interaction between Congruency and Task-Switch frequently appeared, revealing larger switching cost in the incongruent condition as compared to the congruent condition (D. Gopher et al., submitted, Experiment 2). However, this trend was not always significant (e.g., Fagot, 1994; Meiran, 1996; Monsell et al., 1998; and D. Gopher et al., submitted, Experiment 1). Fifth, the triple interaction between Congruency, Task-Switch and CTI almost never reached statistical significance (e.g., Fagot, 1994; Meiran, 1996; Rogers & Monsell, 1995). Hence, preparation reduced switching costs at approximately the same rate in the congruent and the incongruent condition. One implication of that result is that task preparation (at least in the context of frequent task switches) does not involve the activation and suppression of stimulus-response (S-R) translation rules. If task preparation involved these processes, one would expect that it would reduce congruency effects. The reason is that congruency effects are believed to reflect the operation of irrelevant S-R translation rules. Contrary to this prediction, congruency effects sometimes increase by preparation (e.g., Meiran, 1996, Experiment 4). Finally, there was an interesting two-way interaction between Response-Repetition and Task-Switch. In the no-switch condition, response-repetition lead to facilitation, as would be expected. However, in the switch condition the reverse pattern was obtained, showing that response-repetition led to response slowing (Fagot, 1994; Meiran, 1996; Rogers & Monsell, 1995). The last interaction does not seem to be modulated by preparation time. In other words, the interactions involving Response-Repetition and CTI (or response-stimulus interval, RSI) were insignificant (e.g., Rogers & Monsell, 1995).

## Model

### Components

Following Fagot (1994), the model refers to switching-cost components, each one reflecting different combination of underlying processes. I shall begin by defining the experimental conditions. Let us assume there are two tasks, A and B. The trials in the "task alternation" condition are ordered as ABAB..., (e.g., color naming, word reading, color naming ...), while in the "single task" condition they are ordered AAA... (color, color color...) or BBB... (word, word, word...). To complete the picture, there is also a "mixed task" condition, where

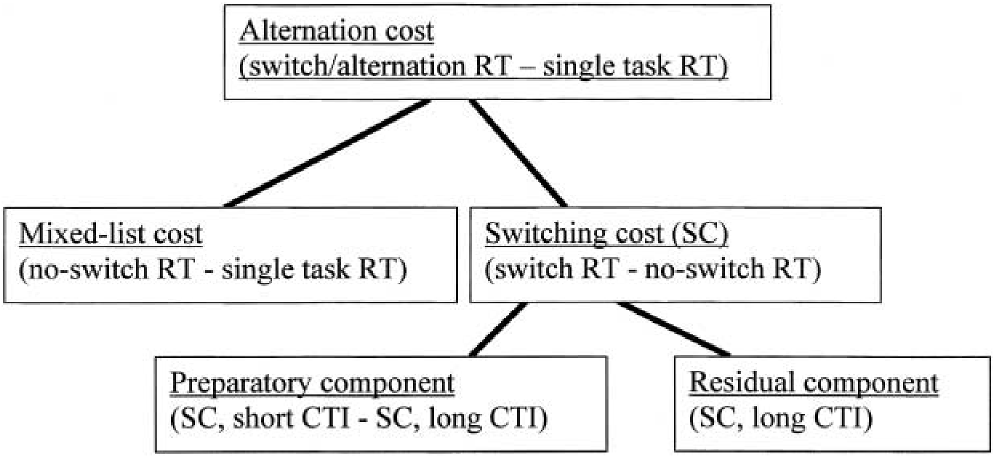

**Fig. 2** Components of the alternation cost (based on Fagot, 1994)

the order of tasks makes it possible to separate switch trials and no-switch trials. An example is the paradigm described in Fig. 1, or that used by Fagot, and, Rogers and Monsell (1995), where the order was AABBAA... The essential feature of the mixed-task condition is that sometimes a task repeats from the previous trial and sometimes it changes. An example for the no-switch condition is the second trial, involving Task B, which comes after another trial involving Task B. An example for a switch trial is the first trial, involving Task B, which comes after a trial, involving Task A.

The division into components is presented in Fig. 2. The most global indicator is the alternation cost, which is the difference in RT between the single-task condition and the alternation condition or the switch condition. Fagot (1994) has shown that the latter two conditions yield similar RTs. The alternation cost has two components. First, the "task switching cost" ("shifting cost" in Fagot's terms) is the difference in RT between the switch condition and the no-switch condition, both taken from the mixed task condition. Second, the "mixed-list cost", is the difference in RT between the no-switch condition and the single-task condition (see also Los, in press-a, in press-b). The task switching cost, in turn, comprises two sub-components, the "residual component" (or "baseline" component in Fagot's terms), which is task switching cost given long preparatory interval (e.g., CTI). The second sub-component is the "preparatory component", which is the difference in the task-switching cost between short preparatory interval and long preparatory interval[1]. While the preparatory component indicates successful task preparation (since the switching cost is reduced), the residual cost indicates preparation failure, since a portion of the switching cost seems to be resistant to task preparation. The results reviewed above indicate that the residual cost is related to Response-Repetition, and weakly related to Congruency. Specifically, Congruency and Response-Repetition interacted with Task-Switch but the triple interactions, which involve these variables and CTI were insignificant. Similarly, Fagot has shown that the mixed list cost is related to Congruency, i.e., Congruency effects were much stronger in the no-switch condition (within the mixed task condition) as compared to the single-task condition.

## Processing aspects: an overview

It is assumed that when stimuli and responses are bivalent, switching between stimulus classification tasks entails a change in the interpretation of stimuli, responses or both. In other words, participants need to think of an upper-left target stimulus as up mainly, or think of the response indicating up and left, as indicating up mainly. The model assumes that these two changes in interpretation are independent of one another and take place at different points in time. These points are embodied in the model depicted schematically in Fig. 3. It is assumed that the physical target stimulus (on the leftmost part of Fig. 3) and the two physical responses (on the top and bottom of Fig. 3) are associated with mental representations (interpretations, placed in the center of Fig. 3). In Fig. 3, Response A indicates up and left, and Response B, indicates down and right. There is a distinction in the model between the response that had been emitted in the previous trial (Prev.R, which is Response A in Fig. 3) and the alternative response (Alt.R, Response B in Fig. 3).

An important concept in the model is task-sets (represented in Fig. 3 as rectangles separating the physical stimulus/responses from their representations). Task-sets govern how mental representations are formed. There are three task sets, a stimulus task set (S-Set), and two response task-sets (R-Sets), Prev.R-Set and Alt.R-Set. The role of the task-sets is to deal with the bivalent aspects of the task. This is done through the biasing of the mental representation in favor of one dimension. For example, applying the appropriate S-Set to the

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[1] Meiran, N., Chorev, Z. & Sapir, A. (in press). Component processes in task switching. Cognitive Psychology suggested a third component, but it will not be discussed here, and the experiment was designed so that the role of the third component would be minimized.

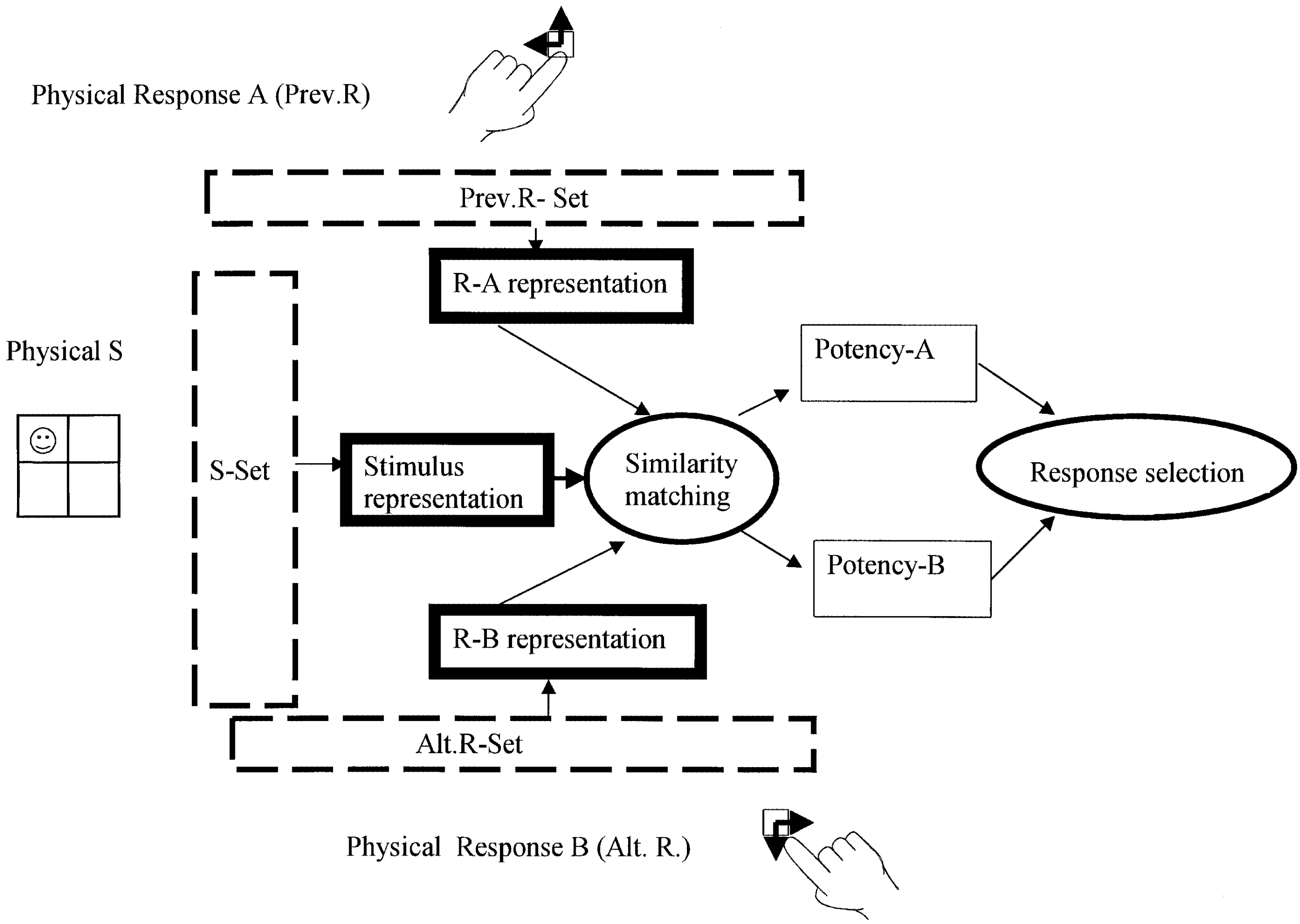

**Fig. 3** The model (see text for details)

upper-left target stimulus results in a mental representation where *up* is emphasized relative to *left*.

Four processes are most important. First, task-sets need to be reconfigured, and second, they need to be applied to form mental representations. The third process is "similarity matching", where the representation of the target stimulus is compared with the representation of the responses. As a result, each of the responses gains "potency" (Potency A, and B, for Responses A and B, respectively, Fig. 3), where potency is determined by the degree of similarity between stimulus representation and the representation of the particular response. The fourth process is "response decision", where response potencies are compared and the more potent response is selected. The processes will be described in the following sections, but I shall begin by outlining the formalism used to describe stimuli and responses.

### *Formal description of stimuli and responses*

Physical target-stimuli and physical responses are represented in the model as a quadruple of zeros and one[2]. The first two numbers describe the vertical dimension (up and down, respectively). The last two numbers describe the horizontal dimension (right, and left, respectively). For example, the pattern "1, 0, 0, 1", represents up-left. When the pattern refers to a target stimulus, it describes a location, such as the upper-left location. When it represents a response, it describes the nominal responses that are indicated by committing that response. For example, the list above describes Response A in Fig. 3 since this response indicates two nominal responses, up and left.

### *Mental representations, stimulus identification, and task-sets*

Mental representations of stimuli and the responses are represented as quadruples of positive fractions, determined by multiplying the elements in the physical stimulus/response (1 or 0) by appropriate weights. The weights serve as task-sets. The S-Set is related to a parameter "$w_S$" ($0 \geqslant w_S \leqslant 1$), representing the bias in favor of the task-relevant dimension in the current trial (Trial N). Accordingly, 1-$w_S$ is the weight assigned to the task-irrelevant dimension (see also Ward, 1982). Applying the S-Set amounts to "stimulus identification". How the S-Set is applied may be clearer considering the example

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[2] Here "physical" may mean pre-attentive.

where the task is up-down, so that the relevant stimulus dimension is the vertical dimension. In that case, $w_s$ may equal 0.95, which implies that the (task-relevant) vertical dimension is much more heavily weighted than the horizontal dimension, i.e., the irrelevant dimension receives a weight of $1\text{-}w_s = 0.05$. Continuing the example, the upper-left stimulus (associated with the list "1, 0, 0, 1") would be mentally represented as "$w_s$, 0, 0, $1\text{-}w_s$", e.g., "0.95, 0, 0, 0.05", with the first two numbers, "0.95, 0" resulting from multiplying "1, 0" (up) by $w_s = 0.95$, and the second two numbers resulting from multiplying "0,1" (left) by $1\text{-}w_s = 0.05$. If the task were right-left, the same physical stimulus would have been mentally represented as "$1\text{-}w_s$, 0, 0, $w_s$", e.g., "0.05, 0, 0, 0.95" (mostly left). Note than in the second example, the numbers representing the vertical dimension, "1, 0" are multiplied by $1\text{-}w_s$, since the vertical dimension is irrelevant, while the numbers representing the (relevant) horizontal dimension are multiplied by $w_s$. In either case, the mental representation is nearly univalent.

Unlike the S-Set, where the weight represents the bias in favor of the task-relevant dimension in Trial N, the weights of the R-Sets represent the bias in favor of the dimension that was task-relevant in Trial N-1. For example, having pressed the upper-left key in Trial N-1 to indicate up, would result in a stronger emphasis of up over left in Trial N which follows. Accordingly, "$w_{Prev.R}$" represents the bias in Prev.R, and "$w_{Alt.R}$" represents the bias in Alt.R ($0 \geqslant w_{Prev.R}, w_{Alt.R} \leqslant 1$). These values represent the biases in the R-Sets during Trial N, but they correspond to the dimension that was task-relevant in Trial N-1. The dimension that was task-irrelevant in Trial N-1 would receive weights of $1\text{-}w_{Prev\ R}$, and $1\text{-}w_{Alt.R}$.

Mental representations of responses are formed in a similar way as mental representations of target stimuli. Moreover, the application of $w_{Alt.R}$ is completely analogous to the application of $w_{Prev.R}$. For example, suppose that Response A in Fig. 3 (which is used to indicate up and left, hence is associated with the pattern "1, 0, 0, 1") has just been emitted in Trial N-1. If the task in Trial N-1 was up-down, the mental representation of that response in Trial N is "$w_{Prev.R}$ 0, 0, $1\text{-}w_{Prev.R}$". In other words, $w_{Prev.R}$ was multiplied by the first pair of numbers in A, "1, 0", representing the vertical dimension. However, if the task in Trial N-1 were right-left, then the response mental representation on Trial N would have been "$1\text{-}w_{Prev.R}$, 0, 0, $w_{Prev.R}$", e.g., "0.45, 0, 0, 0.55". The numbers in the last example indicate a slight bias (0.55) in favor of the dimension that was relevant in Trial N-1, as compared to the alternative dimension, which receives a weight of 0.45 in that example.

### *Similarity matching*

This process determines which response is most similar to the target stimulus, so that a greater degree of similarity results in a relatively potent response. Equation (1) is used to calculate response potency, PA, and PB, for Responses A and B, respectively:

$$P = \Sigma SiRi \quad (i = 1, \ldots, k) \tag{1}$$

(k being the number of elements in a list, 4) which translates into $PA = \Sigma SiRAi$, and $PB = \Sigma SiRBi$, for Responses A and B, respectively.

### *Response decision and RT*

After the determination of response potencies, "response strength" (Str.) is computed as follows:

$$Str. = PA - PB \tag{2}$$

Equation 2 has two consequences: determining which response is selected, and how RT is affected by response competition. The sign of Str. determines which response was more potent, and hence, selected, with positive values indicating that Response A was selected, and negative values indicating that Response B was selected. IStr.I is related to the quickness of the response, hence:

$$RT* = 1/Istr.I \tag{3}$$

With RT* being an analog of RT. Note that the response that had not been selected still affects the value of Str., hence it affects RT*. This aspect reflects the role of response competition, so that a strong competing response results in slower RT.

### *Dynamics of task-set adjustment*

A critical assumption in the model is that the S-Set can be adjusted relatively easily during the CTI, and it must be adjusted prior to stimulus identification for accuracy to be emphasized. This is implemented in the model by assuming that when similarity matching and response decision take place, the S-Set has reached its maximal bias in favor of the task-relevant dimension. In contrast, participants do not adjust the R-Sets during the CTI[3]. The latter assumption is implemented as follows. In the no-switch condition, the R-Sets are biased in favor of the task-relevant dimension (which was also relevant in the previous trial). In contrast, in the switch condition, the R-Sets are adjusted so that the irrelevant dimension is emphasized, reflecting the fact that this dimension was relevant in the previous trial. Note that configuring the R-Sets after response selection is counterproductive because it might make the system ready for the wrong task (i.e., the switch condition). One reason why participants adopt this strategy might be a limitation in the ability to prepare the S-Set and the R-Sets at the same time,

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[3] These assumptions refer to conditions in which task switching involves a change in the relevant stimulus dimension. When task switching involves only the S-R mapping, e.g., de Jong (1995), R-Sets may be adjusted during the CTI. One reason might be that it is difficult for participants to adjust the S-Set and the R-Sets at the same time, and in these cases they prefer to adjust only the S-Set.

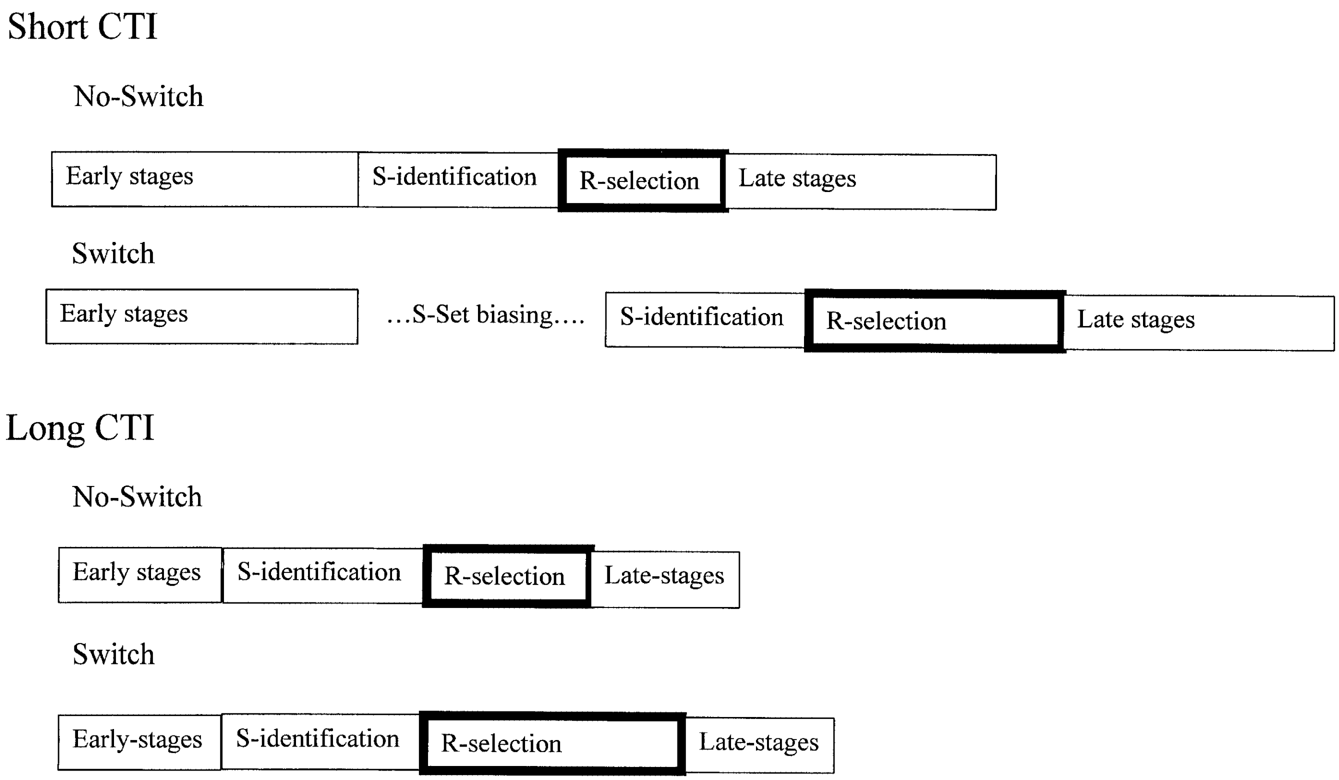

**Fig. 4** Processing stages affected by task-switching

coupled with the relative ease in S-Set configuration. Having chosen a strategy of configuring the R-Sets after response selection, the best strategy for the participant while frequently switching tasks would be to maintain the R-Sets in an unbiased state, i.e., to keep the weights at 0.50. The reason is that with frequent task switching, configuring the R-Sets is counterproductive. The present results indicate that participants manage to approximate the strategy, and barely configure the R-Sets.

The assumption regarding the dynamics of R-Set adjustment can be defended on theoretical grounds. Specifically, Hommel (1997) suggested that responses are coded in terms of their outcomes. Since pressing a response key (e.g., the upper-left key) served to indicate a nominal response the indication (e.g., up) may be considered as the response outcome. Having pressed the upper-left key to indicate up, results in encoding the response as related to up more than to left. The same reasoning does not apply to Alt.R (the response indicating down and right, in the example). Specifically, having pressed the upper-left key would not necessarily result in encoding the lower-right key as indicating down more than right, since that response was not associated with an outcome on that trial. In the present model, I enabled some re-weighting in Alt.R as long as $w_{\mathrm{Prev.R}} \geq w_{\mathrm{Alt.R}}$. In other words, $w_{\mathrm{Alt.R}}$ was a free parameter instead of being forced to equal 0.50 (reflecting no bias). However, the best-fit estimates of the parameters (see below) indicated that $w_{\mathrm{Alt.R}}$ almost equaled 0.50, indicating no bias, as would have been predicted on the basis of Hommel's theory. Finally, it is assumed that both the S-Set and the R-Sets maintain their values from the previous trial[4]. This assumption is reflecting what Allport and colleagues (Allport et al., 1994; Allport & Wylie, in press) called task-set inertia.

### *Processing stages influenced by task-switching*

Following Sternberg (1969) and others, it is assumed that RT is the sum of the durations of processing stages. According to the model, task switching influences two processing stages, S-Set biasing and response selection (which includes similarity matching and response decision). Figure 4 depicts the processing stages in four conditions, determined by CTI and Task-Switch. "Early stages" refer to perceptual processes preceding stimulus identification, such as feature extraction, while "late stages" refer to processes taking place after response selection and related to response preparation. Note that the duration of the early and late stages (reflected by their length in Fig. 4) is unaffected by Task-Switch but one or both stages may be shortened by CTI. In contrast, the duration of the stimulus (S) -identification stage is influenced neither by CTI, nor by Task-Switch.

S-Set biasing takes place in the switch condition only (given the assumption that in the no-switch condition, the S-Set is already biased in favor of the correct dimension). This stage involves changing $w_s$ according to

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[4] The values may go through a decay process immediately after the response, which pushes them towards an unbiased value (0.50).

the requirements of the upcoming task. Take for example a condition where the previous trial was right-left and the task in the current trial is up-down. In that case, S-Set biasing involves changing the weights so that $w_s$, which was previously biased in favor of the horizontal dimension, will be biased in favor of the vertical dimension. As will be shown later, sufficiently strong S-Set biasing is necessary to produce correct responses. Hence, for accuracy to be emphasized, S-Set biasing must precede stimulus identification[5].

If the CTI is too short to permit sufficient S-Set biasing, S-Set biasing proceeds after target presentation and adds to RT (and to the switching cost, see the short CTI, switch condition in Fig. 4). However, if the CTI is long, S-Set biasing is completed during the CTI and does not add to RT (the long CTI, switch condition in Fig. 4). In other words, the preparatory component of switching cost, which indicates how much switching cost is reduced by preparation, reflects the duration of the S-Set biasing stage.

### *A description of a trial*

At this stage, the reader is already familiar with the different aspects of the model, and a complete picture of the sequence of events in a trial can be given. The sequence begins when the instructional cue is presented. After the presentation of the cue, an S-Set biasing/configuration process begins. This process takes place during the CTI but continues even if the target stimulus is presented prior to it completion. As soon as the S-Set is sufficiently biased, the S-Set is used to identify the target stimulus, i.e., to form its mental representation. In the next stage, a similarity matching process activates the two responses, so that the more similar response becomes more potent and is selected. Sometime after response selection, a process of R-Set adjustment takes place and determines the R-Sets and the mental representations of the responses for the next trial.

## How does the model account for the results?

*Correct responses.* The most relevant finding with respect to cognitive control is the fact that participants manage to respond according to the required task, most often with perfect or near perfect success. According to the model, correct responding is made possible by a more strongly biased S-Set than R-Set, ideally $w_s = 1$, indicating complete selection of the relevant stimulus dimension, but realistically, the selection is less than perfect. Let us assume for simplicity that selection is perfect. Having represented an upper-right target location as up only by an appropriately biased S-Set, this activates the response which contains up in its code, and does not activate, or barely activates the response which contains right in its code. In other words, correct responding can rely entirely on the S-Set. Since selection is not perfect, there are boundary conditions for correct responding.

Specifically, the S-Set needs to be more strongly biased that the R-Sets, that is, $w_s > w_{\mathrm{Prev.R}}$, and $w_s > w_{\mathrm{Alt.R}}$. The reason is that, in the incongruent condition, the target stimulus activates both responses. For example, an upper-right target has a shared feature (up) with the response indicating up and left, and it has a shared feature (right) with the response indicating down and right. If the task is up-down, the former response is correct and the latter response is incorrect. Hence, correct responding depends on a greater potency of the former response as compared to the latter response. The reader may notice that, in Equation 2, potency is largest when the same dimension is emphasized in the stimulus representation and the response representation. Given the assumptions that the S-Set is determined by the current task, while the R-Sets are determined by the previous task, this happens in the no-switch condition. However, in the switch condition, the relevant dimension is emphasized in the S-Set, but the irrelevant dimension is emphasized in the R-Sets. In that case, the more strongly emphasized set determines which response is more potent, hence selected. Therefore, the S-Set (which reflects current task demands) must be more strongly biased than the R-Sets.

*CTI × Task-Switch.* This interaction reflects the fact that task-switching cost is reduced by preparation, namely, the preparatory component. According to the model, the preparatory component of switching cost reflects the duration of the S-Set biasing stage, which adds to RT given short CTI (Fig. 4).

*Residual costs.* This effect reflects the prolongation of the response selection stage in the switch condition. This happens because, in the switch condition, the irrelevant response features are emphasized and the relevant response features are de-emphasized. As a result, the correct response becomes “less similar” to the target stimulus, leading to lesser potency and longer RT. Moreover, in the case of response competition (see below), the competing response becomes more similar to the target stimulus, leading to stronger competition, and slower correct RTs.

*Congruency.* In “correct responding” I have already given an example showing that, in the incongruent condition, the target stimulus activates both responses. This does not happen in the congruent condition. For example, an upper-left target activates the response indicating up and left, because of the two shared features, but that target has no features in common with the alternative response. Hence, the congruent condition yields faster responses for two reasons. First, there is no

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[5] In the present model, stimulus encoding refers to relatively abstract, “deep”, codes, not to feature extraction. These codes are so abstract that they can interact with response-related codes.

competition from the alternative response, and second, both the relevant target feature and the irrelevant target feature activate the correct response. As one may notice, Congruency effects are expected only when there is less than perfect selection. If the participants had managed to bias the S-Set completely this would have resulted in the elimination of congruency effects. The reason is that the irrelevant feature would no longer be included in the mental representation of the target stimulus and would no longer activate the responses.

*Task-switch × Congruency.* In the switch condition, the irrelevant dimension is emphasized in the R-Sets, and the relevant features are de-emphasized. This accentuates congruency effects relative to the no-switch condition. The main reason is that compared to the no-switch condition, in the switch condition there is a greater degree of competition in the incongruent condition because the irrelevant response feature is emphasized. Consequently, the wrong response is more strongly activated, leading to slower correct responses in that condition.

*Task-Switch × Response-Repetition.* This finding is easily explained given the assumption that responses are coded after responding. Consider a sequence of trials where Trial N-1 involved the up-down task and the participant pressed the upper-left key to indicate up. Consequently, the code for the upper-left response key was adjusted, giving more emphasis to up (e.g., 0.6) than to left (e.g., 0.4). Since the lower-right key was not pressed in Trial N-1, its code was either adjusted more moderately than that of the upper-left key (e.g., 0.55 and 0.45) or was not adjusted at all (0.5:0.5).

After switching to the right-left task in Trial N, repeated selection of the upper-left response key would be relatively difficult as compared to selecting the lower-right key press. This is because left is more strongly de-emphasized in the response code corresponding to the upper-left key (0.4 in the example) than right is in the code of the lower-right key (0.45 or 0.5). This explains why response repetition in the context of task switching is associated with response slowing. If, however, Trial N involves task repetition, repeating the response would lead to facilitation since the relevant interpretation is emphasized in the response. Following the example above, repeated pressing of the upper-left key to indicate up would be facilitatory, since up is relatively strongly emphasized in the mental representation of the response. (see Rogers & Monsell, 1995, for a similar account).

## Model-fitting and parameter estimation: an illustration

The model was fit to results from an experiment in which the participants performed the paradigm described in Fig. 1 in three 1-h sessions. In Sessions 2 and 3, single-task blocks and mixed-task blocks were interleaved where half of the participants performed the up-down task and half performed the right-left task. The single-task condition included several peculiar aspects, for reasons that are irrelevant in the present context. Hence the main analysis concentrated on the mixed-task condition.

### Method

*Participants.* Twenty-four undergraduate students from Ben-Gurion University participated in the experiment as a part of a course requirement. They all reported normal or corrected-to-normal vision. Half of the participants were assigned to each response-key combination: either upper-left and lower-right (as presented in Fig. 1) or upper-right and lower-left.

*Apparatus and stimuli.* All testing was performed with an IBM-PC clone with a 14" monitor. The stimuli were drawn in white on black and included a 2 × 2 grid that subtended a visual angle of approximately 3.4° (width) × 2.9° (height). The target stimulus subtended approximately 0.3° (width) × 0.5° (height). The arrowheads subtended approximately 0.3° × 0.3°, and were positioned 0.7° from the end of the grid.

*Procedure.* There were three 1-h sessions. The first session consisted of four identical mixed-task blocks of 150 trials each. Sessions 2 also comprised of four blocks of 150 trials each, but the blocks were ordered mixed-tasks, single-task, mixed-tasks, single-task. In Session 3 there were three blocks, ordered as mixed-tasks, single-task, mixed-tasks. The participants were encouraged to get up and stretch a little between blocks. The keyboard, used to collect responses, was positioned so that its keypad was aligned with the center of the computer monitor. Each trial in the switch blocks consisted of: (1) an empty grid presented for a constant RCI of 1432 ms; (2) the presentation of the instructional cue for a variable CTI (166, 416, and 1,016 ms); and (3) the presentation of the target stimulus until the response. Beeps of 400 Hz for 100 ms signaled errors. Half of the participants performed the up-down task in all the single-task blocks, while the other half performed the right-left task. Trials in the single-task blocks included instructional cues with the two extreme CTIs only. On half of the trials, the cues matched the required task (e.g., right-left cues in the context of the right-left task) and on the other trials the cues conflicted with the task. This peculiar feature of the design reflected our original questions (to be reported in a separate paper) and would not be discussed further.

### Mixed-task results

*Reaction time.* Five independent variables were included in the analysis of variance (ANOVA): Response-Key (between participants), Task-Switch, Congruency, CTI and Response-Repetition (within participants). The mean RT in each experimental condition was computed after excluding the first trial in a block, trials preceded by errors and trials preceded by RTs longer than 3000 ms (all these criteria led to losing 4% of the data). Of the remaining accurate trials, trials where RT was shorter than 100 ms or longer than 3000 ms were analyzed for accuracy but not for RT (less than 0.3% of the data). Only accurate RTs were analyzed. Because of the random assignment of trials to conditions, and because the conditions differed in error rates, the mean number of nonmissing valid RTs per condition ranged between 46.6 and 57.6. Alpha level was 0.05.

Response-Key was not involved in any significant source of variation. There were three significant main

**Table 1** Mean RT (ms) and PE (*RT* reaction time, *PE* percent error, *CTI* cue-target interval, *S* switch, *NS* no-switch)

| Key | Response | CTI (ms) | Incongruent | | Congruent | |
|---|---|---|---|---|---|---|
| | | | S | NS | S | NS |
| Up-right<br>Down-left | Different | 116 | RT 871 | 761 | 749 | 673 |
| | | | PE 0.08 | 0.03 | 0.00 | 0.01 |
| | | 416 | RT 731 | 690 | 591 | 602 |
| | | | PE 0.06 | 0.03 | 0.00 | 0.00 |
| | | 1,016 | RT 687 | 665 | 564 | 567 |
| | | | PE 0.03 | 0.02 | 0.01 | 0.00 |
| | Same | 116 | RT 870 | 741 | 771 | 632 |
| | | | PE 0.08 | 0.02 | 0.00 | 0.00 |
| | | 416 | RT 761 | 655 | 668 | 566 |
| | | | PE 0.06 | 0.04 | 0.00 | 0.01 |
| | | 1,016 | RT 696 | 630 | 572 | 542 |
| | | | PE 0.03 | 0.02 | 0.00 | 0.00 |
| Up-left<br>Down-right | Different | 116 | RT 765 | 705 | 662 | 603 |
| | | | PE 0.08 | 0.03 | 0.02 | 0.03 |
| | | 416 | RT 701 | 651 | 556 | 546 |
| | | | PE 0.05 | 0.03 | 0.00 | 0.00 |
| | | 1,016 | RT 646 | 647 | 527 | 522 |
| | | | PE 0.05 | 0.04 | 0.00 | 0.00 |
| | Same | 116 | RT 822 | 695 | 731 | 557 |
| | | | PE 0.10 | 0.05 | 0.02 | 0.01 |
| | | 416 | RT 743 | 612 | 586 | 514 |
| | | | PE 0.08 | 0.06 | 0.01 | 0.01 |
| | | 1,016 | RT 664 | 597 | 554 | 513 |
| | | | PE 0.06 | 0.04 | 0.01 | 0.00 |

effects, including Congruency $F(1, 22) = 57.25$, $MSE = 30{,}443.86$; CTI $F(2, 44) = 69.69$, $MSE = 11{,}563.49$; and Task-Switch $F(1, 22) = 46.50$, $MSE = 13{,}779.17$. These main effects were involved in three two-way interactions, including Response-Repetition and Task-Switch $F(1, 22) = 58.36$, $MSE = 2{,}524.33$, Congruency and Task-Switch $F(1, 22) = 6.75$, $MSE = 1{,}771.42$, and CTI and Task-Switch, $F(2, 44) = 23.75$, $MSE = 3{,}372.43$. There was also a significant triple interaction between Congruency, CTI, and Task-Switch $F(2, 44) = 4.86$, $MSE = 1{,}223.48$, but the size of this interaction was considerably smaller than that of the other significant effects. A planned contrast indicated a significant residual switching cost, i.e., the simple main effect of Task-Switch was significant even when only the longest CTI was included in the analysis, $F(1, 22) = 15.93$, $MSE = 2{,}439.13$. Vincentized RT (not shown) indicates that switching cost was larger among the relatively slow responses. Consequently, switching cost was approached virtually zero among the fastest responses (5th percentile) given long CTIs.

*Errors*. The mean error rate was low (2.8%), and 50.5% of the cells had zero errors. Hence, an ANOVA may not be justified here. Nonetheless, we conducted the analysis mainly to detect trends suggesting a speed-accuracy tradeoff. As in the RT analysis, Response-Keys was not involved in any significant source of variation. The following main effects were significant, Response-Repetition $F(1, 22) = 4.72$, $MSE = 0.0007$; Congruency $F(1, 22) = 28.69$, $MSE = 0.0087$; CTI $F(2, 44) = 7.75$, $MSE = 0.0015$; and Task-Switch $F(1, 22) = 20.28$, $MSE = 0.0015$. There was a significant two-way interaction between congruency and response-repetition, $F(1, 22) = 4.65$, $MSE = 0.0008$. In addition, there was a triple interaction between Congruency, Task-Switch, and CTI, $F(2, 44) = 6.09$, $MSE = 0.0009$. These variables were also involved in a number of two-way interactions.

It appears that the triple interaction reflected a floor effect in the congruent condition. For example, collapsing the data across response-keys and response-repetition, to explore the triple interaction revealed that in the congruent condition, the error rate ranged between 0.3% to 1.3%, and there were barely any switching costs (−0.1% in the first two CTIs and 0.2% in the last CTI). In contrast, the error rate in the incongruent condition ranged from 3.0% to 8.5% and the switching costs declined with increasing CTI from 5.3% through 2% to 1.3%.

Similarly, when the two-way interaction between Congruency and Response-Repetition was explored, it was found that, in the congruent condition, the mean error rate was unaffected by Response-Repetition (0.7% in both cases). However, in the incongruent condition, response-repetition increased the error rate from 4.3% to 5.3%. Most importantly, the analysis did not reveal a trend for speed-accuracy tradeoff.

## Model implementation

The model was implemented in a Microsoft EXCEL spreadsheet. It is reasonable to assume that RT* (model output) and RT are monotonously related, which was implemented as a linear relation for simplicity. For this

**Table 2** Modeling results (RT, ms): observed values are pooled across response-keys (*R* response)

| Response | | CTI(ms) | Switch | | | No-switch | | |
|---|---|---|---|---|---|---|---|---|
| | | | Observed | Predicted | Difference | Observed | Predicted | Difference |
| Different R | Incongruent | 116 | 818 | 821 | −3 | 733 | 741 | −8 |
| | | 416 | 716 | 699 | 17 | 671 | 676 | −5 |
| | | 1,016 | 667 | 659 | 8 | 656 | 654 | 2 |
| | Congruent | 116 | 705 | 710 | −5 | 638 | 631 | 7 |
| | | 416 | 573 | 589 | −16 | 574 | 566 | 8 |
| | | 1,016 | 546 | 549 | −3 | 545 | 544 | 1 |
| Same R | Incongruent | 116 | 846 | 856 | −10 | 718 | 707 | 11 |
| | | 416 | 752 | 734 | 18 | 633 | 642 | −9 |
| | | 1,016 | 680 | 694 | −14 | 613 | 620 | −7 |
| | Congruent | 116 | 751 | 740 | 11 | 594 | 603 | −9 |
| | | 416 | 627 | 618 | 9 | 540 | 538 | 2 |
| | | 1,016 | 563 | 578 | −15 | 527 | 516 | 11 |

reason, fitting the model was accomplished by maximizing the Pearson correlation between RT* and RT, using EXCEL Solver. Several sets of starting values were tried to ensure that Solver found a global optimum, rather than a local optimum.

### *Auxiliary assumptions and additional parameters*

Although only three parameters are of main interest, two additional parameters were included. First, it is known that instructional cues elicit nonspecific preparatory processes that influence performance in the switch condition and the no-switch condition alike. Such "general" preparatory processes include alertness (e.g., Posner & Boies, 1971; Chorev & Meiran, 1998; Rogers and Monsell, 1995; and N. Meiran et al., in press, for studies related to task-switching) and the prediction of target onset (e.g., Niemi & Naatanen, 1981, for review; N. Meiran et al., in press, for a study on task switching). Hence, $P_{NS}$ was included as an additional parameter, reflecting the preparatory facilitation in the no-switch condition as a proportion of the facilitation in the switch condition. The second free parameter refers to the size of the preparatory switching Cost $P_{Prep}$. This parameter expresses the preparatory cost as a proportion of RT in the best prepared state, i.e., long CTI and no-switch. Specifically, in the long CTI, RT was predicted on the basis of Equation 3. In the short CTI, it was computed in the same manner, except that there was an addendum. Formally:

$$\begin{aligned} \mathrm{RT}* = {} & 1/|\,\mathrm{str.}| + \\ & \quad 0 \quad (\text{long CTI}) \\ & \text{or RT} *_{\text{no-switch,longCTI}} \times \mathrm{P_{Prep}} \times \mathrm{P_{NS}} \\ & \quad (\text{short CTI, no-switch}) \\ & \text{or RT} * \text{no-switch, long CTI} \times \mathrm{P_{Prep}} \\ & \quad (\text{short CTI, switch}) \end{aligned} \tag{4}$$

It was possible to fit the model using the two extreme CTIs (and this was done successfully), although it left only 16 data points to be fit. To improve the ratio of data points to free parameters, the results of the intermediate CTI (416 ms) were also included in the fitting process. It was assumed that the intermediate CTI corresponds to 75% preparation. In other words, when the CTI was 416 ms, $P_{Prep}$ was multiplied by 0.25. This value was chosen based on previous results. These results indicate that most of the effect of CTI is obtained with CTI around 400 ms with little further improvement as a result of additional increase in CTI (e.g., Meiran, in press; N. Meiran et al., in press).[6]

### *Model fitting and modeling results*

Fitting was applied to mean RTs after collapsing across Response-Keys, i.e., the conditions were formed by the combination of Congruency, Task-Switch, Response-Repetition and CTI. After fitting, the correlation between RT* and RT was $r = 0.994$. Since Pearson correlation reflects the fit of a linear model, the parameters of the linear regression were used to translate RT* to RT, and the results are presented in Table 2 and Figs. 5–7[7]. The root-mean-square deviation between observed RT and predicted RT was 9.8 ms. One should not be overwhelmed by the high correlation, given the ratio of free-parameters (5) to data points (24). The best fit values for the three "interesting" parameters were $w_s = 0.970$, $w_{Prev.R} = 0.509$ and $w_{Alt.R} = 0.501$.

There are several things to note regarding these parameter estimates. First, $w_s$ was close to 1, indicating that the selection of the relevant dimension in the S-Set was nearly complete. Furthermore, $w_{Prev.R}$ and $w_{Alt.R}$, which bias in favor of the previous task relevant dimension, were very close to 0.50, which represents

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[6] An alternative strategy could have been to include an additional free parameter, but given the number of free parameters, I chose to select a value on a priori grounds.

[7] Note that the regression equation has two free parameters, but these parameters were not part of the model fitting process proper, and were only used for the purpose of presentation.

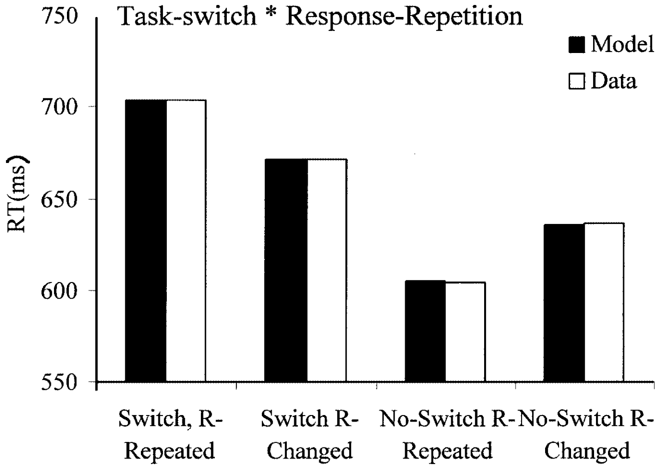

**Fig. 5** Task-Switch by Response-Repetition: model predictions and data

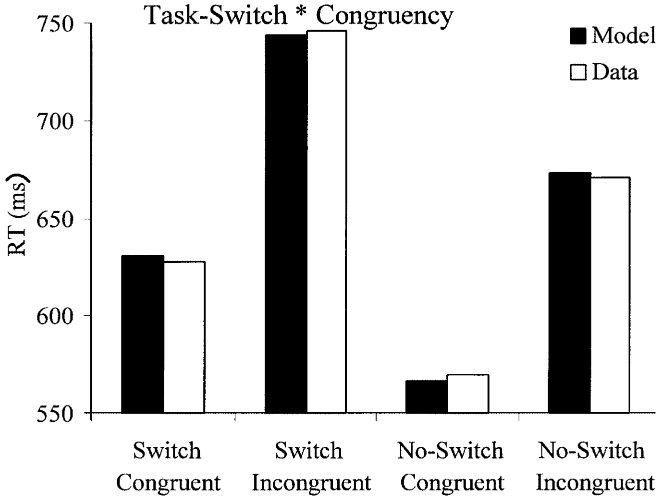

**Fig. 6** Task-Switch and Congruency: model predictions and data

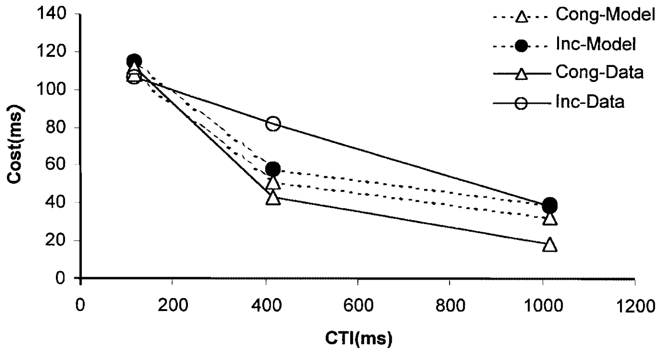

**Fig. 7** Task-Switch by Congruency by CTI: model predictions and data (*Cong* congruent, *Incong* incongruent, *CTI* cue-target interval)

an unbiased state, i.e., almost no selection at all in the R-Sets. $W_{\text{Prev.R}}$ indicated a slight bias in favor of the previously relevant dimension when the response repeated (hence, Prev.R) but not when it changed (hence, Alt.R). These values are extremely close to what might be conceived as the perfect strategy, with near complete bias in the S-Set (as required to reach a low error rate, see above), and barely any bias in the R-Sets.

Second, although the estimates were based on RT data exclusively, the value for $w_s$ was such that a very low error rate was expected (see "correct responding" above), as found. Third, the ability of the model to account for the interactions between Task-Switch, Congruency, and Response-Repetition was based on the fact that the selection in the S-Set, although nearly complete, was not complete (see "Congruency" above). This was coupled with the slight bias in $w_{\text{Prev.R}}$ (see Task-Switch × Congruency above). Had there not been a bias at all, there would not have been an interaction between Task-Switch and Congruency, and between Task-Switch and Response-Repetition. In both cases, the interactions reflect the fact that R-Sets were determined in the previous trial.

With respect to the "less interesting" parameters, $P_{NS}$ was estimated as 0.536, indicating that the facilitation in the no-switch condition was about half that in the switch condition. $P_{\text{Prep}}$ was 0.091, reflecting that the duration of the S-Set biasing stage (preparatory component) was about 9% of the RT in the no-switch-long CTI condition.

At a qualitative level, it can be concluded that the model accounts very well for the interactions between CTI and Task-Switch[8], as well as Task-Switch and Response-Repetition. The results and the model both indicated a similar average reduction in switching costs because of increasing the CTI (Fig. 7). In Fig. 5 it is shown that response repetition was associated with facilitation in the no-switch condition and with response slowing in the switch condition. The model accounted for this interaction almost perfectly. However, the model predicted that switching cost would be slightly larger in the incongruent condition than in the congruent condition, and that this difference would not be affected by CTI (Fig. 7, dotted lines). This prediction was not confirmed, since there was a triple interaction between CTI, Congruency and Task-Switch (Fig. 7, solid lines). Specifically, switching cost was unaffected by congruency in the shortest CTI, and the effect of Congruency on switching cost in the longer CTIs was much larger than predicted. I wish to note that the results of the present experiment may be considered as an exception, since most previous results were much closer to the model predictions. In any case, the direction of the triple interaction suggests an increased response (and task) competition with increasing CTI. This result is certainly inconsistent with models, which assume that CTI is used to reconfigure S-R translation rules.

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[8] Being able to account for the Task-Switch by CTI interaction is the least surprising outcome. The reason is that one parameter is devoted exclusively to explain the interaction.

## Accounting for mixed-list costs

The present model explicitly states that when participants switch rapidly between tasks, complete readiness is not achieved because the R-Sets remain relatively unbiased (with R-Set weights being roughly 0.50). In contrast, when participants perform in a single task condition, a stronger bias is expected in the R-Sets. Consequently, stimulus representations would be more similar to the representation of the correct responses, correct responses would be associated with higher potencies, and RT would be faster. Hence, the model accounts for the presence of mixed-list costs. Furthermore, the model predicts that in the single-task condition, Congruency effects, which reflect the weight given to the irrelevant dimension, would be relatively small. In other words, the model predicts that mixed-list costs would be related to Congruency as found by Fagot (1994). The notion in the present model that complete readiness is not achieved in the no-switch condition stands in sharp contrast to other models. For example, Rogers and Monsell (1995) suggested that complete readiness for a given task is achieved after the first execution of the task (especially Experiment 6, see also Fagot; and D. Gopher et al., submitted).

### *Fitting single-task results*

In the present section, I tested whether the account of the mixed-list cost is consistent with the results in the single-task blocks. The analysis should be regarded tentative because the single-task blocks had several peculiar features, unrelated to the focus of the present article. The results were analyzed according to Response-Key (between participants), Congruency, CTI and Response-Repetition (within participants). There was a significant main effect of Congruency, $F(1, 22) = 32.22$, $MSE = 1669.49$, and a significant interaction between Congruency and CTI, $F(1, 22) = 6.15$, $MSE = 217.99$. Congruency effects were somewhat larger in the long CTI, 45 ms (471 vs 426 ms) than in the short CTI, 36 ms, (467 vs 431 ms). I do not offer an explanation for interaction. However, the more important results are the much faster responses (445 ms in the single-task blocks vs 620 ms in the no-switch condition, an effect of 175 ms), and much smaller congruency effect as compared to the switch blocks. In the no-switch condition within the mixed-task blocks, the congruency effect was 101 ms (671 vs 570 ms, see above), while in the single-task blocks it was 33 ms. In addition, the main effect of Response-Repetition was insignificant in the single-task blocks ($p = 0.08$), but it indicated a trend toward faster repeated responses, as found for the no-switch condition in the mixed-task blocks. Only the main effect of Congruency reached significance in the analysis of errors, $F(1, 22) = 11.86$, $MSE = 0.0007$, reflecting more errors in the incongruent condition (1.4%) than in the congruent condition (0.2%).

In fitting the results, I used the linear regression parameters which were used to translate RT* to RT in the modeling of the mixed-tasks results above. Four instead of five free parameters were estimated, with a new parameter reflecting the effect of CTI on RT in ms. This parameter was eventually chosen to be zero. In other words, CTI had no influence whatsoever on RT, in contrast to what has been found in the mixed-task condition. This is an interesting feature but I suspect it is related to the fact that the instructional cues were misleading in half of the trials and participants were encouraged to ignore them. The other three parameters assumed best fit values of $w_s = 0.988$, $w_{Prev.R} = 0.538$ and $w_{Alt.R} = 0.536$. The fit was reasonable $r = 0.979$, root-mean-square deviation = 3.5 ms, and maximal deviation 5.9 ms.

In spite of the limitation of the present analysis, due to the peculiarities of the design, it sheds light on the mixed-list costs. First, these costs result from a stronger bias in the R-Sets, close to 0.54:0.46 as opposed to only 0.51:0.49 in the switching blocks. In addition, the degree of bias in the S-Set was stronger than in the task-switching blocks (0.988 vs 0.970). In other words, consistent execution of the same task results in a better selection of the relevant stimulus dimension.

Since S-Set biasing explains part of the mixed-list cost, it was interesting to examine its contribution relative to that of the R-Sets. Therefore, I estimated how changing the parameter values affects predicted RT. In doing so, all parameters but one parameter retained the best-fit values found in the single-task blocks. One parameter value was changed to the best-fit value found in the mixed-task blocks. Changing the S-Set from 0.988 to 0.970 resulted in an increase in mean predicted RT from 455 ms to 477 ms. In other words, the stronger emphasis in the S-Set accounts for 22 ms of the mixed-list cost which was 175 ms. Changing the R-Sets to their value in the mixed-task blocks resulted in considerable slowing, 104 ms slowing. Although this analysis is limited because it ignores the contributions due to the interactions between the parameters, it points to the much larger contribution of the R-Sets in causing the mixed-list cost as compared to the S-Set.

Another important issue is the asymmetry often found between facilitation and interference in congruency effects (e.g., MacLeod, 1991, regarding the Stroop task). To examine this issue, I compared the simulated results of the congruent condition and the incongruent condition to a neutral condition in which the target stimulus included the relevant dimension only. The ratio of interference (incongruent minus neutral) to facilitation (neutral minus congruent) was 1.02, indicating near symmetry. However, with a more poorly biased S-Set (as supposedly happening in the Stroop task) such as $w_s = 0.6$, the ratio of interference to facilitation was 3.7. In other words, the present model attributes the asymmetry of facilitation and interference to poor bias in the S-Sets.

## Discussion

### Novel predictions

In my opinion, predictive utility and less so explanatory power should be considered in judging empirical models. Here I shall mention three novel predictions. Successful tests of the first two predictions are reported in a previous study (Meiran, in press). First, the model explicitly suggests that the preparatory switching cost reflects the duration of the S-Set biasing stage. S-Set biasing is required only when the stimuli are bivalent, not when they are univalent. Hence, the model predicts that, with univalent target stimuli, switching cost would be entirely comprised of the residual component.

The second prediction refers to the residual switching cost. According to the model, residual costs arise because of the counterproductive adjustment of the R-Sets taking place after response selection. When the responses are univalent, that is, each key-press indicates only one nominal response, such as up, the R-Sets are completely biased in favor of one dimension. In other words, R-Sets are neither adjusted, nor do they affect switching costs. Hence, with univalent responses, the residual cost is predicted to be absent.

The third prediction is related to the influence of speed-accuracy emphasis on the preparatory switching cost component. Specifically, the prediction is that the size of the preparatory component and error rate would be negatively correlated. The reasoning is as follows. First, according to the model, the preparatory component of switching cost reflects the duration of the S-Set biasing stage. Furthermore, it is reasonable to assume that if the S-Set biasing stage is prolonged, this results in a stronger bias in favor of the relevant stimulus dimension. Second, the model relates the bias in the S-Set to response accuracy, with a stronger bias related to fewer errors. More precisely, errors are predicted to take place in the incongruent condition (see above). For this reason, the difference in error rate between the incongruent condition and the congruent condition is related to the strength of the bias in the S-Set. Hence it was predicted that the size of the preparatory component would be negatively related to the difference in error rate between the incongruent and the congruent condition. This prediction was confirmed in an as-yet-unpublished study by manipulating speed-accuracy emphasis (N. Meiran and A. Daichman, Patterns of errors in task switching, in preparation). In the present experiment, the across-participant correlation between the two variables was $-0.31$, $p = 0.14$, which is in the predicted direction but, given the small number of participants (for correlational analyses), was insignificant.

### Generality

To be considered as a general model, it must fit results from a variety of experimental paradigms. This is because there is evidence that task differences, and quite likely, differences in instructional cues as well (e.g., de Jong, 1997), affect performance. The fact that the model explains results that were found in a variety of paradigms might indicate that the model is incorporating general principles. For example, a critical assumption is that participants do not bias the R-Sets during the CTI. With such biasing, CTI is expected to reduce the size of the congruency effects. Nonetheless, such a trend is commonly absent or even reversed in many studies (Fagot, 1994; Meiran, 1996; Rogers & Monsell, 1995). Similarly, the interaction between Task-Switch and Response-Repetition, in the absence of significant interactions of these variables with CTI also cuts across paradigms (Fagot, 1994; Meiran, 1996; Rogers & Monsell, 1995). Finally, mixing tasks results in slower responses and larger congruency effects (Fagot, 1994; and the present study).

Another important issue concerns the fact that, strictly speaking, the model applies to tasks involving uni-dimensional perceptual discrimination of multi-dimensional target stimuli. These include the present tasks, shape and color decisions (e.g., Hartley et al., 1990) and perhaps Stroop task switching (Allport et al., 1994). In these instances, participants are required to attend to one stimulus dimension, while ignoring other dimensions, and cognitive control can be mediated by S-Sets. However, there has been considerable research on switching non-perceptual tasks including arithmetic operations (e.g., "+5"), semantic memory retrieval (e.g., giving the opposite to words), and same-different judgments. It remains to be determined whether switching tasks involves similar processes regardless of which tasks are being used. A candidate process is selective attention in its broad sense. This includes non-perceptual tasks, where selection is based on directing attention to memory retrieval (e.g., in sense, Neely, 1977). Generally, it is suggested that control over the information being fed into the response selection process may prove to be more important in dynamic control than the re-programming of response selection. Such reprogramming may require more time or effort than available in paradigms involving rapid task switching.

### Relationship to other models of task switching

#### *Accounts of residual costs*

De Jong (in press) recently challenged the presence of residual costs. He suggested that residual costs reflect the fact that participants do not prepare themselves on all trials, but when they do, there are no residual costs. Due to averaging the results from "prepared" trials and "unprepared" trials, residual costs are observed in mean RTs. Support for this interpretation comes mainly from two observations. First, when given sufficient time to prepare, switching costs are seen among the relatively long RTs, but not among the relatively short RTs. This observation may be interpreted as showing complete readiness on some but not all of the trials. Second, the RT distribution in the switch condition with long CTI can be successfully modeled as a weighted combination of two other distributions. These include the distribution of RTs in the short CTI, switch condition, representing the fully unprepared state, and the RT distribution in the long CTI, no-switch condition, which represents the fully prepared state.

In the present model, residual costs result from the counterproductive update of the R-Sets (especially $w_{\mathrm{Prev.R}}$ ) after response selection. The present model may be compatible with de Jong's (in press) results (but perhaps not with de Jong's model). For example, it could be the case that updating of the R-Sets takes place on some trials where the next trial would involve a residual cost. On other trials, there is no updating, and the trials following them would not involve residual costs. In other words, the present model can account for the presence of two populations of trials, but for different reasons than specified by de Jong. The present model may be preferred because, in addition to an apparent ability to account for de Jong's results, it also explains the interactions involving Task-Switch, CTI, Congruency and Response-Repetition. It also accounts qualitatively for additional results and has several nontrivial predictions.

### *Relation to S-R translation terminology*

The present terminology deviates somewhat from the terminology used by several other investigators. I preferred the current terms mainly because this enabled me to link the model to action coding theories (Hommel, 1997; Prinz, 1997). This made it possible to account for the interactions involving congruency and response-repetition, which is in the heart of the model. In any case, it is desirable to point to possible equivalents. For example, response mental codes may be viewed as S-R translation rules since they map stimulus attributes to physical responses. Similarly, R-Sets may be viewed as relative activation of sets of S-R translation rules (in the sense offered by Shaffer, 1965, and Duncan, 1977). One could think of two S-R mappings. In Mapping 1, the upper-left stimulus and the upper right stimulus are mapped to the upper-left key, and the lower-right and lower-left stimulus are mapped to the lower-right key. In Mapping 2, the upper-right and the lower-right stimuli are mapped to the lower right key, and the upper-left and lower-left stimuli are mapped to the upper-left key. Moreover, Mapping I and Mapping 2 may both be activated, although to different degrees, which is roughly analogous to a biased R-Set.

S-Sets reflect the selective attention mode. Put differently, they may be viewed as adjustable filters that screen out (most of) the information regarding the currently irrelevant stimulus dimension. By adjustable I mean that what information is screened out, and to what degree, can be adjusted or changed. The role of the S-Set, according to this formulation, is to control which stimulus information is fed into response codes (or S-R translation rules).

If the link between the present terminology and S-R translation terminology is accepted, this implies that participants maintain all S-R mappings equally activated and control responses by selective attention, which governs the input of the S-R rules. The present model is therefore drastically different than several other models of task switching. These models suggest that participants are able to prepare S-R translation rules (J. Rubinstein, et al. in press), that task switching involves a switch in S-R rules (e.g., Allport et al., 1994) or programming of the response-selection stage (Fagot, 1994).

### Limitations

It should be noted that the mathematical formulation of the present model is almost indifferent to whether the S-Set or the R-Sets are prepared during the CTI. Hence, the fact that the model fits the data well may not be considered as strong support for the assumptions regarding the dynamics of set adjustment. To relate preparation unequivocally to the S-Set and the residual component to the R-Sets, it is necessary to show an empirical dissociation, as done by Meiran (in press, see "novel predictions" above).

The second limitation concerns the relationship between the verbal descriptive level and the particular instantiation in mathematical equations. In the present article, only one possible instantiation was explored. It might be the case that a different set of equations that fits the verbal description just as well as the current set of equations would not yield such a close fit to the data.

### Challenges

Although the model faired reasonably well in explaining the present results, it is still in its infancy. For example, the model potentially applies to accuracy results but these results were not modeled. Specifically, if it were assumed that the S-Set bias changes from trial to trial, this could explain why errors occurred and why they occurred almost exclusively in the switch-incongruent condition. Namely, when on a given trial the S-Set was less biased then the R-Sets, this resulted in selecting the wrong response. The model should also be fit to additional sets of results, especially from other task-switching paradigms. The present modeling attempt also raises many new questions. For example, it is suggested that the preparatory component of switching cost reflects the duration of S-Set biasing. If so, this stage takes 60–70 ms. Why then does it take over 400 ms to bias the S-Set during the empty CTI? One possibility is that stimuli cue the relevant task sets, as suggested by Allport et al. (1994), and Allport and Wylie (in press). Specifically, the combination of the instructional cues and the target stimulus may act as a much stronger cue to retrieve the relevant task set.

Another challenge to the model is the presence of congruency effects in Stroop task switching (e.g., Allport et al., 1994). I suggest, tentatively, that the fact that the same utterances were used for colors and color-words may be roughly equivalent to bivalent responses with R-Sets equally biased (0.5:0.5). Namely, a given utterance is equally primed by colors and color words. For example, the utterance *red* corresponds equally to the word RED and to the color *red*. Consequently, selective attention to stimulus dimensions dictates exclusively which response will be primed. When the S-Set is incompletely biased, information from the irrelevant word dimension activates competing responses giving rise to congruency effects.

The present modeling attempt was restricted to switching between two tasks. Hence attending to one dimension implied inattention to the other dimension, and emphasizing one response interpretation implies de-emphasizing the alternative interpretation. In other words, inattention/de-emphasis and attention/emphasis are symmetrical. However, recent evidence by Mayr and Keele (in press), who studied switching between more than two tasks, suggests that inattention/de-emphasis and attention/emphasis are not symmetrical. The authors have shown that switching back to a just-abandoned task resulted in slower responses as compared to switching to a task that was not just abandoned. These results will be taken into account when the model is extended to multi-task situations.

Finally, Los (in press-a; in press-b) has shown that switching between perceptual operations entails a cost that is immune to task preparation. These results may be consistent with the present model by assuming that the S-Sets (selective attention to stimulus dimensions) operate upon outputs of perceptual operations, but the operations themselves are not primed by attention. This includes attention to memory retrieval, which presumably mediates switching between arithmetic operations.

## Conclusions

The present article described a model of task switching performance that offers a reasonably accurate account for the pattern of interactions of task-switch, response-repetition, congruency and CTI, as well as the mixed-list cost. The results of the present experiment show that the best fit values of the parameters approximated rational behavior, given the assumed limitations imposed on preparation. The model is based on the assumption that trial-to-trial task control is mediated by selective attention.

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