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ORIGINAL ARTICLE

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Task switching: on the origin of response congruency effects

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Abstract When people frequently alternate between simple cognitive tasks, performance on stimuli which are assigned the same response in both tasks is typically faster and more accurate than on stimuli which require different responses for both tasks, thus indicating stimulus processing according to the stimulus–response (S–R) rules of the currently irrelevant task. It is currently under debate whether such response congruency effects are mediated by the activation of an abstract representation of the irrelevant task in working memory or by "direct" associations between specific stimuli and responses. We contrasted these views by manipulating concurrent memory load (Experiment 1) and the frequency of specific S–R associations (Experiment 2). While between-task response congruency effects were not affected by the amount of concurrent memory load, they were much stronger for stimuli that were processed frequently in the context of a competitor task. These findings are consistent with the idea that a large portion of the congruency effects stems from direct S–R associations and they do not support a sole mediation by task-set activation in working memory.

Introduction

A prevalent theme in research on human cognition is how cognitive processes are influenced by internal and external factors. While some processes seem to be confined to the presence of a corresponding action goal, other processes seem to run off regardless of current goals whenever certain environmental conditions are given. Recent cognitive literature provides numerous examples of attempts to understand the interplay of such intentional and unintentional processing (e.g., Hommel, 2000; Pashler, et al., 2001).

In task-switching situations, effects of processing dependent as well as independent of a current task goal can be clearly observed (Allport, et al., 1994; Fagot, 1994; Goschke, 2000; Hoffmann, et al., 2003; Hübner, et al., 2004; Mayr & Keele, 2000; Meiran, 1996; Rogers & Monsell, 1995). In typical task switching experiments, participants have to respond to the same (kind of) stimuli while frequently alternating between two different tasks, for instance, they have to decide whether a stimulus number is odd or even versus whether it is smaller or larger than five. It is widely supposed that participants adopt different task-sets in order to accomplish the varying tasks. In this context the term task-set refers to an internal configuration that relates the task-relevant stimuli to their corresponding responses, thereby ensuring task-appropriate performance on a given stimulus (Mayr & Keele, 2000; Rogers & Monsell, 1995).

The most profound (and from everyday experience hardly surprising) finding in such task switching experiments is that participants can respond with high accuracy with regard to the S–R mapping of one task now and then with regard to the S–R mapping of a different task despite equivalent external stimulation, thus demonstrating flexible task-set shifts.

However, it has been shown that in task switching situations, performance not only depends on the currently relevant task-set, but is also influenced by the set of the temporarily irrelevant task. This can be most clearly seen in the finding that stimuli which are assigned different responses under the two task instructions (incongruent stimuli) yield longer RTs and higher error rates than stimuli that are assigned the same response

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under both task instructions (congruent stimuli) (e.g., Fagot, 1994; Meiran, 1996; Rogers & Monsell, 1995). This congruency effect presumably reflects response activation according to the irrelevant task's S–R rules, resulting in performance decrement due to response conflict in the incongruent case and/or facilitation due to parallel activation of the same response in the congruent case.

To date, it is unclear by what precise mechanisms congruency effects are brought about – especially whether the mechanisms refer to working memory processes or not. One straightforward assumption holds that not only the S–R rules of the relevant task but also the irrelevant task's S–R rules are held active in working memory to some degree. In this conception, task selection would be achieved by increasing activation of the relevant task-set and/or decreasing activation of the irrelevant one (e.g., Meiran, 2000).

An alternative view was presented by Mayr and Kliegl (2000). These authors postulate that only one of the two competing task-sets can be active in working memory at a time. In their account, congruency effects arise from "exogenously cued retrieval of the irrelevant long-term memory (LTM) response code at the time of stimulus presentation" (Mayr & Kliegl, 2000, p. 1138) independently of working memory operations. Support for this view may be derived from a study by Hommel and Eglau (2002). Using a dual-task paradigm, these authors found that processing a stimulus attribute in a primary task was influenced by its compatibility with a secondary response to a different stimulus feature (e.g., RTs in the primary task were faster when the relevant stimulus attribute was the color red and the secondary response required to say "red" rather than "green"). This so-called backward compatibility effect suggests that S–R activations of both tasks took place in parallel. Importantly, the size of the backward compatibility effect was not affected by the amount of concurrent working memory load, thus arguing against the idea of working memory-mediated translation of the stimulus into the secondary response. For this reason, Hommel and Eglau (2002) favored an interpretation in terms of direct S–R links outside working memory which emerge with practice. Such direct S–R links might also be the origin of response congruency effects in task switching situations.

To summarize, response congruency effects under conditions of frequent task switching may, theoretically, arise from either activation of a competing task-set in working memory or practice-dependent formation of direct S–R links. While in dual-task situations, empirical evidence favors the latter interpretation, the situation in task switching still awaits empirical clarification. In the current study we attempt to shed light on the origin of congruency effects by manipulating concurrent memory load (Experiment 1) and the frequency of specific S–R couplings (Experiment 2). If congruency effects stem from the presence of an irrelevant task-set in working memory, they should interact with conditions that draw on working memory capacity, whereas the manipulation of S–R frequency should not influence congruency effects. In contrast, response activation via a direct S–R link should be unaffected by working memory demands, but be highly sensitive to the strength of the specific S–R link, thus resulting in more pronounced congruency effects for stimuli that have been presented more frequently in the context of the competitor task.

Experiment 1

The procedure of Experiment 1 was closely modeled after the above-mentioned study by Hommel and Eglau (2002). That is, we examined congruency effects in task-switching situations under conditions of high- and low-working memory demands. To this end, participants frequently alternated between two tasks, while additionally maintaining a smaller or larger list of items. The two tasks to be switched between were to decide whether a digit between 1 and 9 was smaller or larger than 5 (magnitude task) and whether it was odd or even (parity task). Participants used the same pair of response keys for both tasks, resulting in congruent and incongruent stimuli. Each experimental trial comprised, first, memorizing the order of a list of either two (low demands) or five (high demands) letters, then, responding to two successive number tasks – in which congruency effects were determined – and, finally, reproducing the letter list learned at the beginning of the trial. If congruency effects result from response activation according to the irrelevant task-set remaining in working memory, they should be influenced by working memory load. Thus congruency effects should be larger in the low demands than in the high demands trials. If however, congruence effects are not brought about by activation of the competing task-set in working memory, the working memory load variation should have no influence on the size of the congruency effects.

Method

Participants

Two female and 18 male students of the Helmut-Schmidt University/University of the Federal Armed Forces Hamburg participated in partial fulfilment of course requirements. They ranged in age from 22 to 26 years.

Apparatus and stimuli

The experiment was administered on an IBM-compatible personal computer. Stimuli for the two number tasks were the numbers 1, 2, 3, 4, 6, 7, 8, and 9. They were presented in the center of the screen and extended 1.0 cm vertically and between 0.4 and 0.7 cm horizontally. For both tasks responses were given by pressing the "<" key and the "-" of a standard

QWERTZ keyboard with the left and right index or middle finger. Regarding the magnitude task, participants pressed the "<" key if the imperative stimulus was smaller than 5 and the "-" key if the imperative stimulus was larger than 5. Regarding the parity task, half of the participants pressed the "<" key if the imperative stimulus was odd and the "-" key if the imperative stimulus was even. This assignment was reversed for the other half of the participants. Stimulus presentation for each of the number tasks was preceded by a task cue which appeared slightly above the position of the upcoming stimulus. The cues were the German words "kleiner/größer" (smaller/larger) and "gerade/ungerade" (odd/even), respectively. The cues extended 0.8 cm vertically and 8.6 cm horizontally. Stimuli for the concurrent memory task were the letters B, C, D, F, G, H, and J. They were presented in the center of the screen and extended 1.1 cm vertically and between 0.5 and 0.8 cm horizontally. All stimuli, cues, and prompts were presented in light gray color on a dark gray background.

Procedure

Participants sat approximately 50 cm from the screen. Each experimental trial comprised the following sequence of events. First, the items of the to-be-learned letter list were presented one after another, each for 1 s. The number of letters were either two or five, randomly chosen. If two letters were presented, those were the letters B and J. If five letters were presented, those were the letters C, D, F, G, and H. Participants were instructed to remember the letters in the order as presented. The order of letter presentation was chosen randomly. After the last letter of a to-be-learned list disappeared from the screen, participants were prompted to press the space bar in order to continue. One thousand five hundred milliseconds after the space bar was pressed, the imperative stimulus for the first number task was presented. We refer to the first and second number task in a trial as the prime and probe task, respectively. On each trial, both magnitude and parity decisions had a 50% chance of being presented as the prime task. The task cue appeared 500 ms after pressing the space bar and 1,000 ms in advance of the onset of the imperative stimulus. The number stimulus was chosen randomly from the stimulus set, resulting in a 50% probability that the stimulus was congruent or incongruent. Both task cue and imperative stimulus disappeared from the screen as soon as a response was given. Five hundred milliseconds later, the cue for the second number task (i.e., the probe task) appeared. Successive number tasks in a trial were always different, that is, when the prime task involved magnitude decisions, then the probe task involved parity decisions and vice versa (thus the second task cue was redundant). The imperative stimulus of the probe task was chosen randomly with the only constraint that it needed not be identical with the stimulus of the preceding prime task, and was presented 1,000 ms after the onset of the task cue. Again, task cue and imperative stimulus disappeared from the screen when the response was given. After the response of the probe task, participants were prompted to key in the letters of the learned list in the order of their original presentation. Participants entered the letters via the standard keyboard and signaled to have finished by pressing the Return key. Before pressing the Return key they were free to correct their input. When the list was reproduced correctly, that is, the correct letters in the right order, the next trial started 1,000 ms later. In case of a reproduction error, the word "falsch" (false) was presented slightly below the location of the reproduced letter list for 2,500 ms. The next trial started 1,000 ms later. The "falsch"-feedback was also presented for 500 ms after a false response was given to the prime or probe task. After some practice with the tasks, participants worked through 12 blocks each of which consisted of 20 trials. In between blocks, they were allowed to rest for some time.

Results

About 2.1% of the two-letter list and 14.6% of the five-letter list were reproduced incorrectly. For the RT analysis of the number tasks, we used only RTs of trials in which all tasks, that is, both number tasks and the memory task were responded to correctly. In addition, RTs deviating more than three SD from the mean RT of each participant (1.8%) were considered outliers and also excluded from the analysis. In an analysis of variance (ANOVA) with the within-subject factors Task Order (prime, probe), Task (magnitude, parity), Congruency (congruent, incongruent), and Memory Size (two, five) on the mean RTs of the number tasks, the main effects of Task Order, Task, and Congruency were significant (see Fig. 1). This was because probe tasks were responded to 41 ms faster than prime tasks, $F(1, 19) = 4.06$, $p < .05$, MSE = 28,962.1, magnitude decisions were 64 ms faster than parity decisions, $F(1, 19) = 18.58$, $p < .01$, MSE = 17,882.0, and congruent stimuli were responded to 41 ms faster than incongruent stimuli, $F(1, 19) = 44.02$, $p < .01$, MSE = 3,089.2. A concurrent memory load of five items increased RTs by 19 ms as compared to a concurrent memory load of two items, thereby just failing to reach significance, $F(1, 19) = 4.01$, $p = .06$, MSE = 6,934.2.

Furthermore, Memory Size interacted with Task Order, $F(1, 19) = 5.16$, $p < .05$, MSE = 2,689.5, because increased memory load delayed responses more for the probe tasks (for 31 ms) than for the prime tasks (for 5 ms). Finally, there was a significant interaction between Task and Congruency, $F(1, 19) = 7.64$, $p < .05$, MSE = 3,250.3, indicating that congruency effects were increased when participants responded to the parity task (59 ms) as compared to the magnitude task (24 ms).

Most importantly with regard to our research question, the size of the congruency effects was not affected

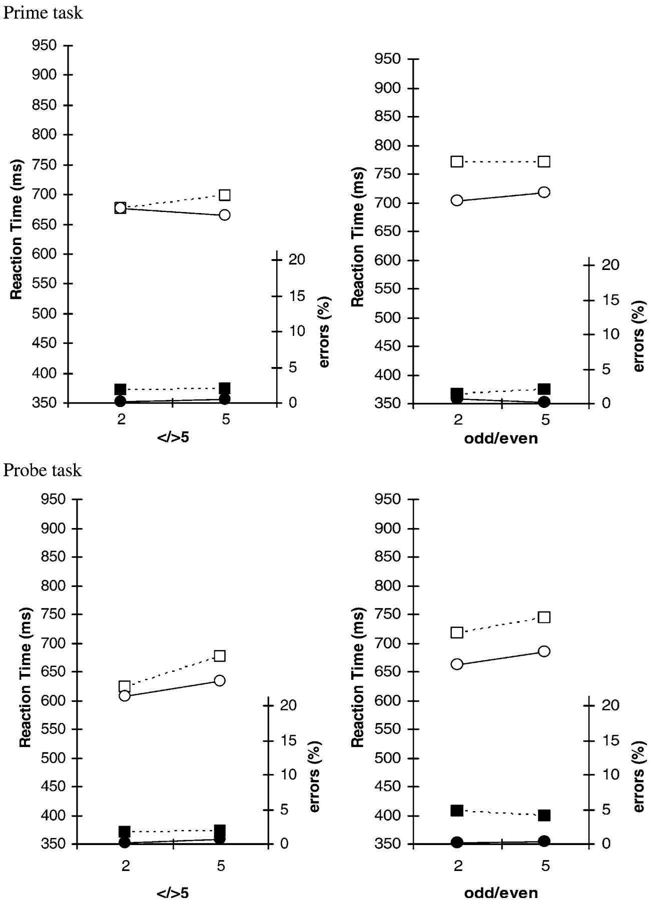

Fig. 1 Mean RTs (*open symbols*) and error proportions (*filled symbols*) of prime (*top panel*) and probe (*bottom panel*) tasks as a function of task (magnitude, parity), memory size (two items, five items), and congruence (*squares* indicate incongruent, *circles* congruent trials)

by the amount of concurrent memory load, $F(1, 19) = 1.06$, $p = .32$, MSE = 2,633.0.[1]

A corresponding ANOVA was conducted on the mean error proportions. Only data from trials in which all other responses were correct were included in this analysis. As for the RT analysis, the main effects of Task Order, Task, and Congruency were significant (see Fig. 1). Probe tasks were associated with 1.7% more errors than prime tasks, $F(1, 19) = 5.77$; $p < .05$; MSE = 0.000610, parity decisions yielded 0.6% more errors than magnitude decisions, $F(1, 19) = 5.05$; $p < .05$; MSE = 0.000529, and incongruent stimuli were associated with 2.0% more errors than congruent stimuli, $F(1, 19) = 14.15$; $p < .01$; MSE = 0.002433. The two-way interaction between Task Order and Task as well as the three-way interaction involving Task Order, Task, and Congruency were significant, $F(1, 19) = 8.07$; $p < .05$; MSE = 0.000396, and $F(1, 19) = 9.82$; $p < .01$; MSE = 0.000477, respectively, because the increase in error proportions for parity decisions as compared to magnitude decisions was confined to incongruent stimuli on probe task. Furthermore, Congruency interacted with both Task Order and Task, $F(1, 19) = 5.03$; $p < .05$; MSE = 0.000711, and $F(1, 19) = 4.61$; $p < .05$; MSE = 0.000730. Congruency effects were more marked for probe tasks than for prime task (difference between error proportions for incongruent and congruent stimuli: 2.7 vs. 1.4%) and more marked for parity decisions than for magnitude decisions (difference between error proportions for incongruent and congruent stimuli: 2.7 vs. 1.4%). Again, congruency effects were not influenced by the size of the memory list, $F(1, 19) < 1$. No other interactions were significant or approached significance.

Discussion

The results of Experiment 1 replicate previous findings. First, participants responded more slowly in prime than in probe tasks replicating Gopher et al. (2000) results that restart costs may exceed switch costs. Second, reliable congruency effects were obtained in both tasks (Fagot, 1994; Meiran, 1996; Rogers & Monsell, 1995), which were larger for the more difficult and less familiar parity task (Sudevan & Taylor, 1987).

Most importantly, increased memory load interfered with overall task performance but had no influence on the size of the congruency effects. Such an influence would have been expected, however, if congruency effects were brought about by the presence of the irrelevant task-set in working memory. More precisely, drawing more on working memory's limited capacity by maintaining a larger set of letters should impair concurrent working memory-mediated S–R translation. Evidence for the notion that increasing the number of to-be-maintained letters from two to five in fact enhanced working memory load and was clearly obtained by the fact that the overall performance in the number tasks was impaired for the larger letter list. Thus, the lacking influence of working memory load manipulation on the size of congruency effects does not support the idea that congruency effects result from irrelevant task-set activation in working memory. To validate the alternative claim that congruency effects arise from direct S–R links Experiment 2 was conducted.

Experiment 2

To validate the claim that direct S–R associations are the origin of congruency effects, we attempted to vary the strength of the specific S–R links by manipulating the frequency of stimuli in a given task. A similar manipulation in a task switching setting was introduced

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[1] Because prime tasks were apparently unaffected by the memory load manipulation, we conducted a separate analysis on probe tasks only. In this analysis, the main effect of memory load was highly significant, $F(1, 19) = 11.21$, $p < 0.01$, MSE = 3,612.7. Again, however, memory load did not interact with congruency, $F(1, 19) < 1$.

by Waszak et al. (2003). In their Experiment 2, participants named either the word- or the picture-constituent of picture–word stimuli. The frequency of the stimuli in the picture-naming task was varied such that a stimulus was either: (a) never presented in the picture-naming task or (b) equally often presented in the picture-naming and the word-reading task or (c) it was four times more often in the picture-naming than in the word-reading task. As a result participants responded increasingly slower on task-switch trials when reading words of picture–word stimuli that were presented more often in the picture-naming task. However, Waszak et al. (2003) only used incongruent stimuli, that is, the words and the pictures always required different responses. Thus, their design does not allow conclusions about congruency effects.

To investigate the influence of a frequency manipulation on congruency effects, in this experiment, participants switched randomly between the magnitude and the parity task. In one task all digits ranging from 1 to 9 (excluding 5) were stimuli, whereas in the other task only four digits (either the digits 1, 4, 6, and 7 or 2, 3, 8, and 9) were presented. If the strength of specific S–R links influences the size of the congruency effects, we expect those digits that were presented in the other task context to produce larger congruency effects than those digits that were not presented in the other task context.

Method

Participants

Thirty-two students of the University of Wuerzburg participated either in partial fulfilment of course requirement or they were paid six euros. Their age ranged from 20 to 42 years (mean 23.1).

Apparatus and stimuli

An IBM-compatible computer equipped with a 17-in VGA-display and the software package E-Prime (Schneider et al. 2002) was used for stimulus presentation and response sampling. Task cues were a square and a diamond with side length of 2.1 cm presented in white on black background. Stimuli were the numbers 1, 2, 3, 4, 6, 7, 8, and 9 extending 0.4×0.7 cm. Task cue and stimuli were presented in the center of the screen, thus the stimulus was presented inside the task cue. For half of the participants all digits were presented for the magnitude task but only a subset of stimuli (either the digits 1, 4, 6, and 7 or 2, 3, 8, and 9) was presented for the parity task. For the other half of participants all digits were presented for the parity task and the subset of stimuli was presented for the magnitude task. Responses were executed with the index fingers of both hands and collected with the "1" and "3" key of the number pad of a standard keyboard. The task cue meaning and the key assignment for both tasks were counterbalanced over participants.

Procedure

Each trial started with the presentation of the task cue. After 200 ms the stimulus was presented. Response times were recorded from the onset of the target until the onset of the response. The next trial started after 1,500 ms had elapsed. Errors were indicated by the German word "Fehler" presented in red together with a beep tone.

Participants performed 15 blocks with 64 trials. In each block 32 trials required the magnitude task and 32 trials required the parity task. For the task with the full stimulus set, each digit was presented four times; for the task in which only the subset of stimuli was used, each digit was presented eight times per block. Each trial was chosen randomly from this trial pool, so that tasks switched randomly.

Results

The first trial of each block and trials following an error (8.3%) were excluded from the analysis as it is not clear whether these trials should be considered as task switch or task repetition trials. RTs deviating more than three SD from the mean RT of each participant (1.5%) were considered outliers and also excluded from the analysis. For the analysis only the task with the full stimulus set was considered (i.e., the factor task was treated as between-subject factor) as half of these stimuli were presented frequently in the other task context (i.e., in 25%), whereas the other stimuli were never presented in the other task context (i.e., 0%). Mean RTs for correct trials and mean percentages of error (PEs) were computed for each participant for each combination of the factors task switch/repetition, congruency (incongruent vs. congruent), and stimulus frequency in the other task (0 vs. 25%).

An ANOVA with the within-subject factors: task switch/repetition, target congruency, target frequency, and the between-subject factor task on the mean RTs revealed main effects for the factors: task switch/repetition, congruency, and stimulus frequency. This was because task repetition trials (694 ms) were responded to faster than task-switch trials (776 ms), $F(1, 30) = 39.97$, $p < .001$, MSE = 428,345.7, congruent stimuli (671 ms) were responded to faster than incongruent stimuli (798 ms), $F(1, 30) = 37.23$, $p < .001$, MSE = 1,027,602.0, and stimuli that were not presented in the other task context (712 ms) were responded to faster than stimuli that were presented frequently in the other task context (757 ms), $F(1, 30) = 21.78$, $p < .001$, MSE = 132,971.9.

Furthermore, congruency interacted with task switch/repetition, $F(1, 30) = 4.36$, $p < .05$, MSE = 6,627.2, and there was a triple interaction of both of these factors with task, $F(1, 30) = 5.45$, $p < .05$, MSE = 8,276.5, reflecting that the congruency effect was more pronounced for task switches (132 ms) than for task repetitions (89 ms) for the magnitude task, whereas for the parity task, the congruency effect was rather high overall (141 ms for task switches and 144 ms for task repetitions). Most importantly, there was an interaction between congruency and stimulus frequency, $F(1, 30) = 20.66$, $p < .001$, MSE = 172,419.1. The congruency effect was increased for stimuli that were presented frequently in the other task context (179 ms) compared to stimuli that were never presented in the other task context (75 ms). Additionally, there was a triple interaction between task switch/repetition, congruency, and stimulus frequency, $F(1, 30) = 7.42$, $p < .05$, MSE = 12,207.1, and an interaction between task switch/repetition, congruency, stimulus frequency, and task, $F(1, 30) = 5.48$, $p < .05$, MSE = 9,017.9. For the magnitude task the influence of stimulus frequency was more pronounced in task switch trials (67 ms for never-presented stimuli compared to 197 ms for frequent stimuli) than in task repetition trials (75 ms for never-presented stimuli compared to 103 ms for frequent stimuli), whereas for the parity task the influence of stimulus frequency was rather high overall (for task switches: 75 ms for never-presented stimuli compared to 208 ms for frequent stimuli; for task repetitions: 82 ms for never-presented stimuli compared to 206 ms for frequent stimuli).

The same ANOVA on error rates revealed significant main effects for the factors task switch/repetition, congruency, and stimulus frequency. Task repetitions (6.5%) were associated with fewer errors than task switches (10.1%), $F(1, 30) = 21.05$, $p < .001$, MSE = 800.5, congruent stimuli (3.7%) were associated with fewer errors than incongruent stimuli (12.9%), $F(1, 30) = 69.29$, $p < .001$, MSE = 5,378.4, and stimuli that were never presented in the other task context (5.9%) were associated with fewer errors than stimuli that were frequent in the other task context (10.7%), $F(1, 30) = 37.02$, $p < .001$, MSE = 1,422.8. Furthermore, the congruency effect was more pronounced in task switch (11.6%) than in task-repetition trials (6.7%), $F(1, 30) = 19.46$, $p < .001$, MSE = 382.6. The interaction between task switch/repetition and stimulus frequency just failed to reach significance, $F(1, 30) = 4.02$, $p < .06$, MSE = 57.5, but descriptively switch costs were increased frequently (5.7%) compared to never-presented stimuli (2.6%). Importantly, congruency effect were increased for stimuli that are frequently presented in the other task context (14.0%) compared to stimuli that were never presented in the other task context (4.3%), $F(1, 30) = 50.44$, $p < .001$, MSE = 1,495.9, for the interaction between congruency and stimulus frequency. For task switch trials the increase of congruency effects for frequent stimuli (17.6%) compared to infrequent stimuli (5.6%) was more pronounced than for task repetition trials (congruency effect for frequent stimuli 10.4% vs. congruency effect for infrequent stimuli 3.1%), reflected by a triple interaction between task switch/repetition, congruency, and stimulus frequency $F(1, 30) = 6.55$, $p < .05$, MSE = 88.6.

Discussion

First, the results of Experiment 2 replicate typical findings of task switching experiments: participants responded more slowly in task switch compared to task repetition trials, replicating the so-called switch costs. Additionally, participants responded more slowly to incongruent compared to congruent stimuli, reflecting the congruency effect. In task switch trials the size of this congruency effect is increased compared to task repetition trials (cf. Fagot, 1994; Meiran, 1996; Rogers & Monsell, 1995).

Most important with regard to the question concerning the origin of congruency effects is the influence of stimulus frequency on the size of the congruency effect. The congruency effect is markedly increased for those stimuli that were presented frequently in the other task context. This increase mainly results from increased RTs and error rates for incongruent stimuli that were frequently presented in the other task context. The effect on congruent stimuli is ambiguous: Stimuli that were

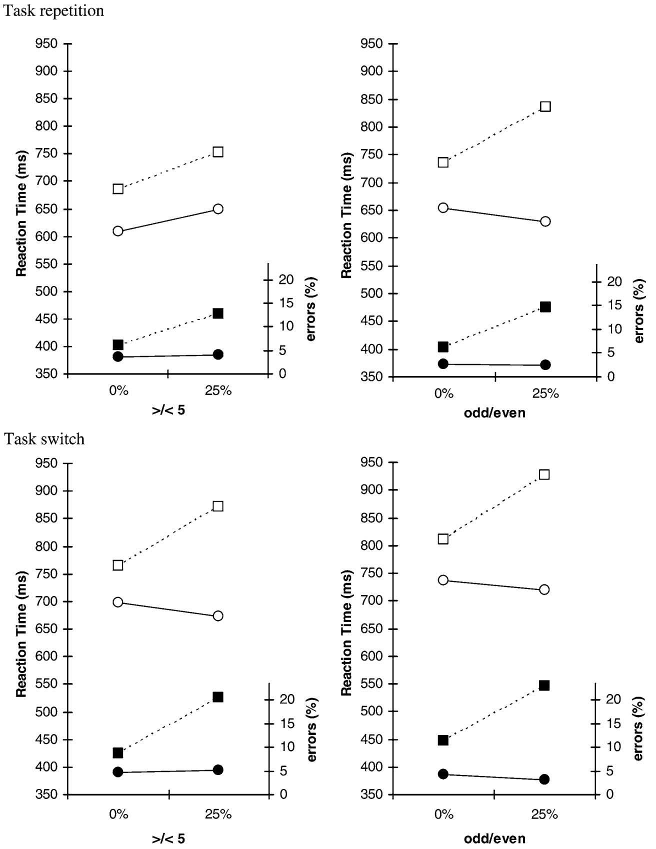

Fig. 2 Mean RTs (*open symbols*) and error proportions (*filled symbols*) for task repetition (*top panel*) and task-switch trials (*bottom panel*) as a function of task (magnitude, parity), stimulus frequency in the other task (0 vs. 25%), and congruence (*squares* indicate incongruent, *circles* congruent trials)

frequently presented in the parity task entailed a slight increase in RTs when they are processed in the magnitude task on task repetition trials (see Fig. 2, top panel, left), but they entailed a decrease in task switch trials (bottom panel, left). In contrast, congruent stimuli that were frequently presented in the magnitude task are processed faster in the parity task for both task repetition and task switch trials. The general pattern of a strong disadvantage for frequently presented incongruent stimuli and only small, if any, frequency effects on congruent stimuli is in line with the assumption that two different processes take place: First, the stimulus that was often processed in the other task context seems to be associated with this task thereby hindering performance of the other, currently relevant task (cf. task cueing effect, Rogers & Monsell, 1995). In addition to this task cueing effect, frequent presentation in a different task also strengthens specific S–R links. These two mechanisms together result in a "double" disadvantage for incongruent stimuli due to both enhanced cueing of the incorrect task and priming of the incorrect response, whereas for congruent stimuli, enhanced cueing of the incorrect task is countered to some degree by enhanced priming of the correct response. Taken together, the influence of stimulus frequency in the other task context on the size of the stimulus congruency effect clearly shows that significant portions of the congruency effect are due to direct S–R associations that have been acquired in the other task context.

General discussion

The present paper addresses the question, which mechanisms are responsible for the occurrence of stimulus congruency effects in task switching experiments. Two different accounts were tested. If congruency effects are due to irrelevant task set activation in working memory they should be influenced by varying concurrent memory load. In Experiment 1, participants performed two different tasks while keeping a sequence of either two or five items in mind. This variation of memory load had no impact on the observed congruency effect thereby making the assumption implausible that congruency effects rely on irrelevant task-set activation in a limited working memory. The second account states that congruency effects are due to direct S–R associations that are formed during the experiment as participants repeatedly perform a particular response according to a given stimulus. If this is true, the frequency of stimuli in one task context should influence the size of the congruency effect in the other task context. In Experiment 2, a subset of stimuli was presented frequently in one task context (the probability for each stimulus was 25%), while another subset of stimuli was never presented in this task context (probability of 0%). This frequency variation had a sizeable impact on congruency effects observed in the other task context. The congruency effect for stimuli that were frequently presented in the other task context was more than double the size of the congruency effect for stimuli that were never presented in the other task context. Hence, huge parts of the congruency effect are due to direct S–R associations.

Interestingly however, there was still a congruency effect for stimuli that were never presented in the other task context (henceforth 0% stimuli). On the assumption that congruency effects are generally brought about by S–R links outside working memory, the generalization to stimuli that never occurred in the context of the other task may be accounted for as follows. First, it is conceivable that responding to a stimulus not only establishes a link between that specific stimulus and the response but also between associated stimuli (i.e., stimuli belonging to the same response category of the current task) and the same response – thus establishing S–R links for stimuli that were never presented. For example, this account holds that the stimulus "3", which was never presented in the magnitude task, nevertheless gets associated with the "smaller" response as it fits to this response category (for similar suggestions see Kunde, et al., 2003; Reynvoet, et al., 2002).

Alternatively, it is conceivable that response activation by a 0% stimulus is brought about in a more indirect manner. There are two different possible mechanisms. First, 0% stimuli may not develop direct associations with a response but with a categorical representation of it. For example, on a magnitude task trial which requires the "smaller" response, all stimuli (or at least those stimuli that have been presented in the experimental context) smaller than five may develop associations with the "smaller" category. Congruency effects for 0% stimuli may then arise from the presented stimulus activating its associated response category (in the other task). Assuming that category–response links have evolved during the experiment, the activated response category will, in turn, activate the corresponding response. Second, stimuli may activate semantically related stimuli. One instance of semantic relatedness is sharing a response category. Thus, a 0% stimulus may activate other stimuli of the response category, some of which — those that have been presented in the other task — activate the corresponding response via their direct links. This account would predict that the stimulus "3" that was never presented in the magnitude task is associated with the digits "1", "2", and "4" as they belong to the "smaller than five category" (likewise it is associated with the digits "1", "7", and "9" as they belong to the category "odd"). If the digit "3" is presented in the parity task some activation spreads to digits which share the same response category in the other task (i.e., 1, 2, and 4). From these digits, those that were presented in the other task context (i.e., 1 and 4 in our experiment) activate the corresponding response, thus causing a congruency effect. Evidence consistent with this view was obtained by Waszak et al. (2004). In that study, impairment in task switching performance found for stimuli which were frequently presented in two tasks generalized to semantically related stimuli which were presented in one task only. Intriguingly, semantic relatedness referred to pre-experimental categories rather than to sharing a common response (the naming tasks used in that study required a unique response for each stimulus).

Deciding between these accounts is beyond the scope of this article. However, some aspects of the results of Experiment 2 at least do not support the idea that responses are activated via semantically related stimuli. Although semantic relatedness may arise for numerous reasons (among them a shared response category), a prominent instance of semantic relatedness with regard to number stimuli can be seen in numerical neighborhood. Of importance with regard to congruency effects, co-activated numerical neighbors might not only activate their corresponding response with regard to the relevant task[2] but also with regard to the irrelevant task. The latter kind of activation, however, should have different impact on congruency effects for 0% stimuli in the parity task and in the magnitude task. Consider first the case of the magnitude task being relevant and the parity task being irrelevant: If the stimulus is congruent (e.g., the number "3" with both the "small" and the "odd" response being on the left side) then — regarding the irrelevant parity task's S–R assignment — the direct neighbors (i.e., "2" and "4") are associated with the incorrect response. In contrast, if the stimulus is incongruent (e.g., the number "2" with "small" on the left side and "even" on the right) then — regarding the irrelevant parity task's S–R assignment — the direct neighbors are associated with the correct response. This additional incorrect response activation on congruent trials and correct response activation on incongruent trials should reduce the congruency effects. In contrast, in the case of the magnitude task being irrelevant the direct neighbors of a congruent stimulus are associated with the correct response (except for the "borderline stimuli" "4" and "6", for which one neighbor, that is, "5", is not linked to any response category), whereas the direct neighbors of an incongruent stimulus are associated with the incorrect response, thereby increasing the congruency effect. To summarize, if the congruency effect on trials with a 0% stimulus is brought about by activation spreading to associated stimuli (which did appear in the other task) and if there are particular associations between direct numerical neighbors then we would expect congruency effects for 0% stimuli to be increased when the magnitude task is irrelevant (and the parity task is performed) as compared to when the parity task is irrelevant (and the magnitude task is performed). As inspection of Fig. 2 shows, however, congruency effects for 0% stimuli do not differ between tasks. Thus, our data do not support the account for congruency effects from co-activation of numerical neighbors, thereby casting doubts on the general idea that congruency effects for 0% stimuli arise from associations with other stimuli which have been presented in the context of the other task.

To summarize, the main question of our study concerned the origin of congruency effects in task-switching paradigms. Our results favor the idea of direct S–R links over working memory-mediated response activation. An open question refers to whether such direct links are also established for stimuli which were never presented in the respective task.

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[2] It is interesting to note that with regard to the parity task the target and its direct numerical neighbors are always of a different parity and thus associated with different responses. In the magnitude task, however, the target and its numerical neighbors are most likely to share the same response category. This might actually be one reason for the typical advantage of the magnitude task over the parity task.

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