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ORIGINAL ARTICLE

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Outsourcing control to the environment: effects of stimulus/response locations on task selection

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Abstract Response-time and accuracy costs as assessed in the context of the task-switching paradigm are usually thought to represent processes involved in the selection of abstract task sets. However, task sets are also applied to specific stimulus and response constellations, which in turn may become associated with task-set representations. To explore the consequence of such associations, we used a task-switching paradigm in which subjects had to select between two tasks (color or orientation discrimination) that were either associated with shared or unique stimulus/response locations on a touchscreen. When each task was associated with unique locations, error switch costs, stimulus–response congruency effects, as well as the characteristic task-switch × repetition-priming interaction were eliminated, and global selection costs were substantially reduced. These results demonstrate that to understand standard task-switching phenomena it is critical to consider links between lower level stimulus/response parameters and task sets.

Introduction

With the exception of low-level reflexes, every action is conditional on representations, often referred to as "task sets", that specify the currently relevant action rules. Over the last decade, questions as to how task sets are selected, maintained, and changed have triggered an impressive body of research with the so-called task-switching paradigm as core experimental tool (e.g., Monsell, 2003). In this paradigm, subjects are required to select among multiple tasks on a trial-by-trial basis. The behavioral costs associated with having to select among competing tasks serve as an indicator of the processing demands involved in configuring the cognitive system to changing situations (Allport, Styles, & Hsieh, 1994; Meiran, 1996; Rogers & Monsell, 1995). Much work in this domain has focused on processes that supposedly operate on the level of competing task sets and allow negotiating between them, such as activation or retrieval of the relevant task aspects (e.g., Mayr & Kliegl, 2003; Rogers & Monsell, 1995) or inhibition of competing tasks (e.g., Mayr & Keele, 2000). Relatively little attention has been given to the influence of task-irrelevant, lower level parameters, such as where in the visual field task-relevant information is presented or task-relevant actions need to be targeted at. In the current work, we will explore to what degree some of the most basic task-switching phenomena may in fact be closely tied to one particular, most frequently used implementation of the task-switching paradigm: namely one in which overlap with regard to low-level, task-irrelevant features is maximal across competing tasks.

It is long known that switch costs are heavily affected by what one could refer to as contextual overlap across tasks. For example, in a classic study by Jersild (1927), substantial switch costs were found when subjects alternated between addition and subtraction operations that had to be applied to digit stimuli. However, switch costs actually turned into benefits when tasks alternated between a simple arithmetic operation that was applied to a digit stimulus and finding the antonym to the word stimulus. In other words, costs of switching are associated with the interference that arises when stimuli are semantically associated with both possible tasks. Given the results by Jersild and others (e.g., Rogers & Monsell, 1995; Spector & Biederman, 1976) on the role of stimulus overlap, one may ask to what degree our emphasis on "lower level" overlap adds anything novel to the picture. We refer to the type of overlap that was manipulated in Jersild's study as semantic (or higher level). It is an overlap between aspects that are inherent to a particular task. For example, it is impossible to devise a subtraction task that is not applied to number

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stimuli. In contrast, with lower level aspects, we refer to aspects that are not inherently related to a task. Rather, these are aspects that arise from the specific, and often arbitrary, spatial–temporal demands of performing a particular task (e.g., see Bryck & Mayr, 2005). For example, in a modern, computer version of Jersild's task, one could either present the digits for both tasks on the same screen location or one could use two different locations, one for each task. The location has no intrinsic association with either task, but it may help to disambiguate between the two tasks. Another example that will be particularly relevant in the current work is that in typical task-switching studies, subjects usually use the same response keys across tasks. Again, there is nothing that would inherently link a particular set of keys to a particular task. However, shared response keys may be a source of interference, just as distinct sets of response keys may help building distinct task-set representations.

The relative neglect of the influence of lower level aspects in task-switching research may have to do with the fact that traditional models of action control emphasized hierarchical control structures where selection on a higher level is largely independent and insulated from selection on lower levels (e.g., Rosenbaum, Kenny, & Derr, 1983). However, there are both functional/theoretical considerations and a number of empirical results suggesting that a strict division between levels of selection may not be tenable. On a functional level, specific tasks are often associated with particular objects (e.g., Creem & Proffitt, 2001) or locations. Thus, our cognitive system might be geared towards exploiting such covariations between task sets and lower level selection parameters (e.g., Waszak, Hommel, & Allport, 2003). Associations between lower level and set-level codes could serve the purpose of "outsourcing" the demanding process of top-down selection and maintaining the relevant setting to lower level representations.

Empirical evidence for between-level integration

Initial empirical results that may be taken as evidence for between-level integration comes in the form of a particular type of repetition-priming effect that is often obtained in task-switching experiments: response repetitions are positive when the task repeats across trials, but turn into costs when the task changes (e.g., Rogers & Monsell, 1995). One interpretation of this pattern is that a task becomes integrated with a particular stimulus or response resulting in interference when the same lower level aspects are paired with a new task on the next trial. While consistent with such an interpretation, the switch × prime interaction could also be interpreted as a strictly lower level phenomenon. Any switch in task usually goes along with a change in attended stimulus aspects so that response repetitions in case of a task switch imply that a response associated with stimulus aspect A will now have to be "rewired" to stimulus aspect B. Indeed, repetition costs are obtained when responses repeat but stimulus aspects change even when no task switching is required (e.g., Marczinski, Milliken, & Nelson, 2003). However, Mayr and Bryck (2005) recently introduced a paradigm in which subjects had to apply one of four different spatial transformation rules to one of four locations arranged in terms of a square (e.g., the "vertical" rule required pressing the lower left key to an upper left object). An important characteristic of this set of rules was that certain S–R associations could occur under two different rules (e.g., both the rule "counterclockwise" and the rule "vertical" requires a lower left response to an upper left object). Thus, here a change in task sets (i.e., rules) did not go along with a change in attended stimulus aspects. The critical question then is to what degree the repetition of an S–R coupling leads to costs in case of a rule switch. Such a result would suggest the integration between stimulus, response, and rule-related codes into a common representation. In fact, this is the result Mayr and Bryck found, thus providing unambiguous evidence that task sets per se can be in some way integrated with lower level stimulus and or response codes.

It is possible that such integration-type effects only occur on a trial-to-trial basis, in which case they would have little relevance for issues of learning and adaptation to a particular task environment. Therefore, it is an important question whether covariation information between low- and high-level aspects also enter long-term memory (LTM). Interesting evidence in this regard comes from a series of experiments reported by Waszak et al. (2003). The basic paradigm required subjects to switch between word and picture naming in a word–picture interference paradigm. The critical manipulation was whether or not pictures used in the word-naming task had been used in earlier trials for the picture-naming task. Interestingly, word-naming switch costs were substantially increased for the pictures used earlier, even when these had been presented many trials ago (and thus clearly had to temporarily reside in LTM). Importantly, this increased cost was even observed when the picture and the word were congruent suggesting that it did not simply reflect interference between competing responses but rather interference between the currently required task set (word naming) and the task set cued by the picture.

Evidence of low-level constraints on task selection

What does the fact that task sets can become associated with specific features of concrete selection instances imply for research on task switching? To what degree does consideration of such effects enforce a reappraisal of important task-switching results? In the introductory section, we had already mentioned why this is an important question. So far, task-switching experiments have been implemented almost always in a way that maximized low-level overlap in the form of the same stimulus locations/objects and response keys across tasks. This procedural choice was probably more a matter of convenience than the result of deep theoretical consideration. However, it raises the question to what degree the large degree of low-level overlap may be a precondition for important task-switching phenomena. This question is the more critical as in many natural situations the same type of overlap does not exist. Thus, it is important to know to what degree standard switching results generalize beyond the typical task-switching situation.

There are actually a few studies that provide first hints regarding the role of lower level overlap on task selection. Meiran (2000) used a paradigm in which subjects judged either the vertical or the horizontal placement of a circle within one of the four corners of a square (see Fig. 1). Responses had to be entered on diagonally arranged keys: the lower left key was used to indicate either the left or the bottom location of the circle; the upper right key was used to indicate either the right or the top placement of the circle. According to Meiran, responses were bivalent in this situation because each key (and finger) had two different meanings (e.g., left position or top position). Using a between-subject design, he contrasted this setup with conditions in which subjects used two different pairs of keys, one for each task. In addition, the two sets of keys where laid out in a manner that was completely compatible with the corresponding perceptual judgment: horizontally for the left–right decision, vertically for the up–down decision. The contrast between bivalent and univalent keys did, in fact, have a strong effect on RT switch costs. In particular, the so-called residual costs (i.e., the costs that remain even after a long preparatory interval) were eliminated. One prevalent interpretation of residual costs is in terms of unwanted retrieval of competing task-representations that are automatically triggered through stimulus or response codes (e.g., Waszak et al., 2003). Thus, this result is consistent with the notion that when distinct low-level features are associated with each task, task representations become more distinct, and as a result, between-task interference is reduced.

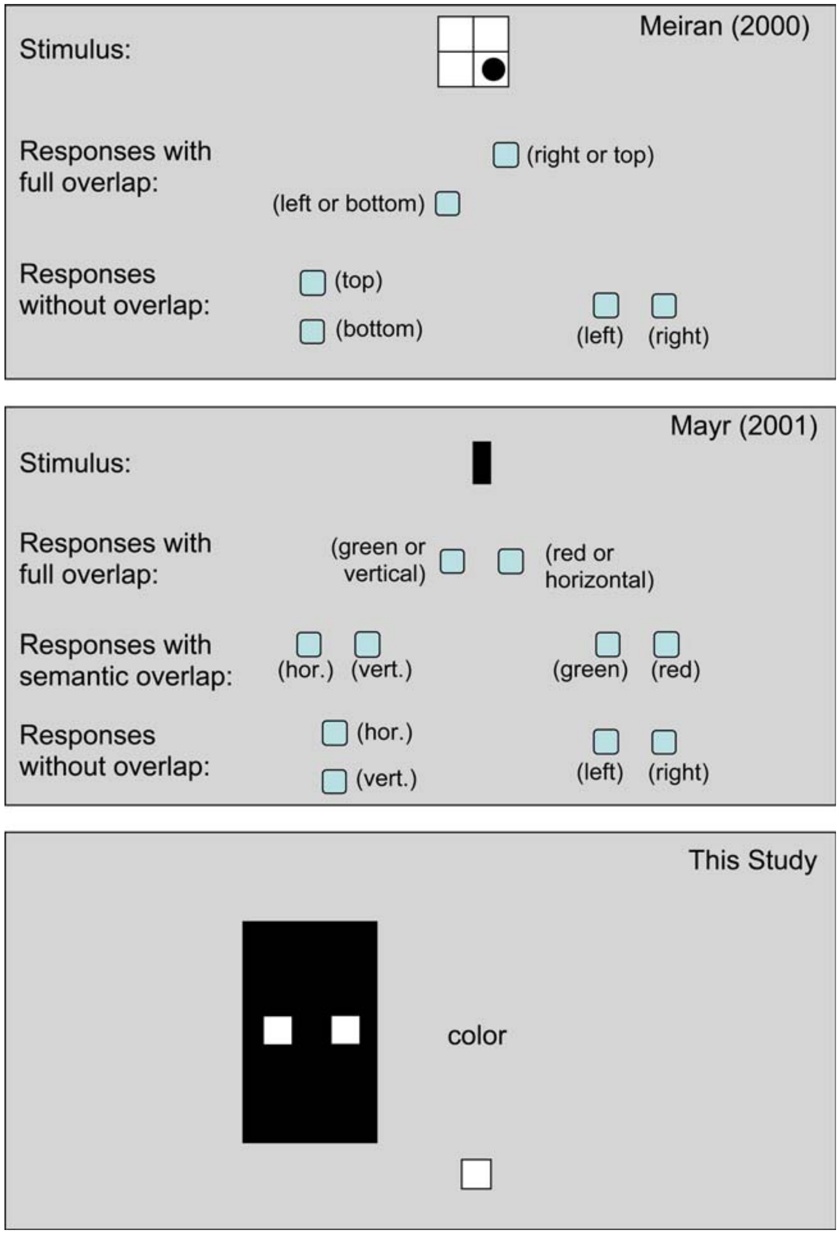
While the results of this study are certainly instructive, the critical manipulation entails a number of confounds that render the conclusions somewhat ambiguous. Specifically, the contrast between the diagonal two-key setup and the four-key setup not only varies key locations (i.e., lower level aspects), but also the degree of high-level, semantic overlap. Whereas in the diagonal two-key setup, each key could be interpreted in terms of either the horizontal or the vertical dimension, each key used in the four-key setup could only be interpreted in terms of a single aspect (see Fig. 1). Low-level and semantic overlap are, in fact, potentially separable aspects in this arrangement, as one could easily imagine a situation with two distinct diagonal set of keys, one for the horizontal task and the other for the vertical task (thus, eliminating low-level overlap but maintaining high-level overlap). Given this confound, it is not clear to what degree the separation in terms of distinct response locations or the separation in terms of meaning was the critical factor behind the reduction of switch costs. Eliminating semantic overlap between the two different tasks by using differentially arranged sets of response keys has also an additional important consequence. Several of the interesting task-switching phenomena, such as across-task response-priming effects (explained above) or congruency effects (to be explained below) may arise exactly because response keys share meaning across tasks (e.g., Schuch & Koch, 2004). Thus, when such overlap is avoided we cannot examine to what low-level overlap contributes to these phenomena.

A study on adult age differences in task-switching situations by Mayr (2001) contrasted, similar to Meiran (2000), a setup with either two keys for both tasks or two keys for each task (judging the color or the orientation of a rectangle; see Fig. 1). However, aside from the full-overlap condition, there were two different conditions with distinct sets of keys for each of the two tasks. In the first, there was meaning overlap across the two response setups (e.g., a left vs. right key had to be pressed for either of the two tasks). In the second condition, meaning overlap was eliminated by using orthogonal arrangements for the two pairs of keys (as in Meiran, 2000). No reliable differences were found for young adults across the three different conditions. However, there were dramatically larger global selection costs (i.e., RT costs when task selection had to occur, no matter whether switch or no-switch trials) for old adults when working with the full-overlap, two-key setup. There was no difference between the two different four-key setups. Given the variations in paradigms, the studies by Meiran (2000) and Mayr (2001) are difficult to compare. However, together they do suggest that at least one important lower level aspect, namely whether or not response parameters overlap across tasks, makes a major difference for the degree of selection difficulty. In addition, the Mayr (2001) study suggests that the amount of actual physical overlap has a unique effect, over and above the effect of meaning overlap.

The present study

In the present study, we attempted to contrast two situations, one modeled as closely as possible after the traditional procedure with full overlap regarding stimulus objects/locations and response objects/locations, the other separating both aspects across tasks. Figure 1 shows our stimulus–response setup. Subjects had to evaluate either the color (red vs. green) or the orientation (horizontal vs. vertical) of a large square that could occur either on the left or the right side of a touchscreen. The critical overlap manipulation was implemented across distinct blocks of trials. In the single-object condition, the stimulus object appeared at a constant loca-

Fig. 1 Simplified presentations of the stimulus–response setups used in Mayr (2001) and Meiran (2000), and in the current experiment. Labels in *brackets* indicate the response assignments, but were not shown on the screen. The study by Meiran (2000) contained additional conditions that are not presented here. For the current study (*lower panel*), the stimulus display shows the central cue and a stimulus object on the left side with the two response areas within the object and the response areas that served as "home key". In the high-overlap condition, a single object/location was used for both tasks (e.g., always on the left). In the high-overlap condition, object locations covaried along with the tasks (e.g., right location for color task and left location for orientation task)



tion (i.e., always on the left), no matter, which task was cued. In the no-overlap condition, the location of the stimulus object covaried with the cued task (e.g., on the left for the color task and on the right for the orientation task).

The use of a touchscreen served two goals. First, we were able to embed the response locations within the stimulus objects (see Fig. 1). This enabled a tight coupling between stimulus and response object/location as is typical in the natural environment where actions are usually targeted at the objects we are attending. Second, this procedure allowed us to avoid a problematic aspect in the studies by Mayr (2001) and Meiran (2000). Their contrast between four-key and two-key setups varied not only the degree of overlap between response locations but also whether two hands, one for each task, or one hand for both tasks was used for responding. Our setup allowed subjects to respond with the index finger of their dominant hand across all conditions. Finally, it is important to emphasize that across the two overlap conditions (single object vs. dual object), subjects worked with the same stimulus object and used the same response setup within the stimulus object. Thus, we manipulated low-level overlap while leaving the higher level overlap unaffected.

To characterize the effects of low-level constraints on some of the basic task-switching effects, we also manipulated two additional factors: stimulus ambiguity (univalent vs. bivalent stimuli) and the cue-stimulus interval (CSI). This design enabled us to assess the following task-switching phenomena:

- *Local switch costs* are obtained by comparing task-switch with no-switch trial-to-trial transitions and reflect the demands of changing a task set. We expect a switch between tasks to be faster and/or less error-prone when supported by a switch in object/location.
- *Global selection costs* (often also referred to as "mixing costs"; Meiran, 2000) are obtained by comparing bivalent-stimulus blocks with univalent-stimulus blocks. Global costs reflect the general demands of endogenous task-set selection independent of whether or not a change in set was necessary. When distinct task-set representations are supported by unique lower level settings, global selection should be reduced.
- *Response congruency effects* are obtained by comparing trials on which both task dimensions require either the same versus different responses and indicate the efficiency with which currently task-irrelevant information is filtered out. Such filtering may be particularly efficient when distinct task-set representations are supported by separate low-level settings.
- *Switch* × response-repetition effects have been mentioned earlier in Introduction as one phenomenon that may be directly linked to the integration of codes participating in a particular selection instance within a common representation (Hommel, 2004). The typical pattern is that of substantial benefits when all codes can be repeated (i.e., task and response), but costs when the response repeats in case of a task switch relative to a situation in which both task and response change. If task-specific integration is actually constrained by low-level features, then we expect that the critical interaction pattern is obtained when these low-level features overlap (i.e., in the single-object condition), but not when there are unique associations between tasks and objects/locations.
- *Preparation effects* are indicated by reduced local switch or global costs for long compared to short CSIs and are often used as an indicator of intentional, proactive control efforts. The critical question here is to what degree endogenous preparation modulates bottom-up effects triggered through low-level parameters.

Method

Participants

Sixteen students of the University of Oregon participated in a two-session experiment in exchange for $14.

Tasks, stimuli, and procedure

Subjects worked on a 17-in., touch-sensitive screen (Elo Touchscreens). Stimulus objects were a rectangle that was oriented along the vertical axis, a rectangle that was oriented across the horizontal axis (for both: long side = 10 cm, short side 5 cm), or a perfect square (side length of 7.5 cm). The color of the stimulus object was either red, green, or white, and it could appear either on the left or the right side of the screen (7.5 cm away from the screen center). The rectangles contained in their center two smaller squares, which served as "response boxes" (2 cm×2 cm). Subjects had to judge either the rectangle's orientation and touch the left key for vertical and the right key for horizontal orientation, or the rectangle's color and touch the left key for green and the right key for red objects. In separate blocks, the stimuli could either be bivalent (i.e., carrying response-relevant information on both dimensions) or univalent (e.g., a white, vertically oriented rectangle when the task is shape). Also, in separate blocks, the stimulus object always appeared at the same location (e.g., always on the left) or the location covaried with the task (e.g., on the left for the color task and on the right for the orientation task). The relevant task was signaled through a verbal task label ("color" or "shape") presented in the center of the screen (font Geneva, size 36). A small square 5 cm below the screen center served as a home key. After each trial, subjects had to rest their index finger on the home key to activate the next trial. In order to reduce variability due to subjects taking varying amounts of time to return to the home key, there was a minimum of a 500 ms pause before which touching the home key could trigger the next trial. Subjects were instructed to use the index finger of their preferred hand for responding.

The sequence of events was as follows: 1,100 ms after activating the home key, the next stimulus occurred. During that interval the task cue appeared either after 100 ms response-cue interval (RCI) and thus with 1,000 ms CSI or after 1,000 ms RCI and thus with 100 ms CSI. Thus, CSI was manipulated while keeping the total inter-trial interval constant (Meiran, 1996). The stimulus and cue were visible until the response. At that point, the home key was brightened in order to prompt subjects to return to it. In case of an incorrect response, a short error tone sounded.

In each session, subjects worked through two sets of 16-trial blocks each. The single-object versus dual-object condition was assigned in a counterbalanced manner to the first versus second half of each 16-block set. Within each half, RCI/CSI, stimulus ambiguity, and object position for the single-object condition (left vs. right) were also counterbalanced. The first session was to acquaint subjects with the touchscreen setup.

Results

We excluded all trials in which subjects did not return to the home key within 1,000 ms after a response (2.2% of trials) and for which RTs were larger than 3,000 ms (0.3% of trials). To compute RTs, we also excluded all error trials and trials after errors.

Turning first to local switch costs, we found that whereas error switch costs were substantial in the single-object bivalent condition, they were eliminated in the dual-object bivalent condition (see Fig. 2, Table 1). The

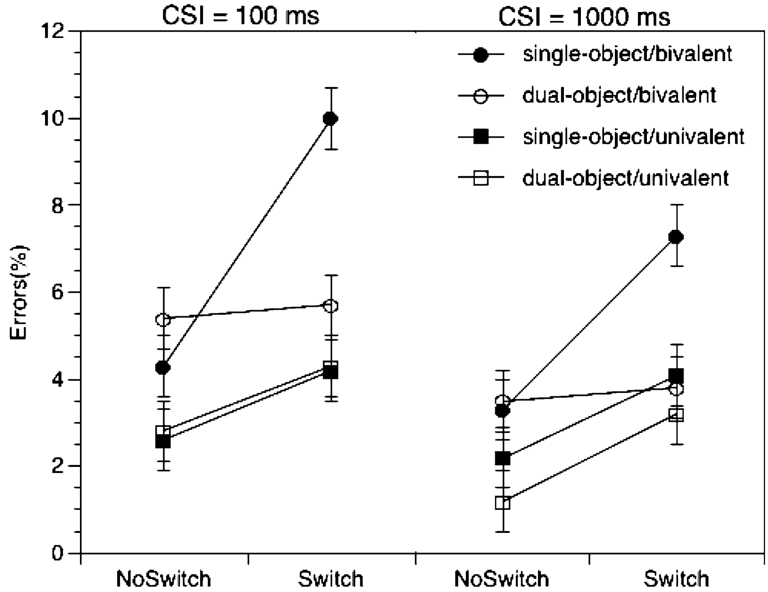


Fig. 2 Error rates as a function of cue-stimulus interval (CSI), single-object versus dual-object conditions, stimulus ambiguity (univalent vs. bivalent), and the switch factor. *Error bars* represent the 95% within-subject confidence intervals for the single–dual-object × univalent/bivalent × switch interaction (Loftus & Masson, 1994)

corresponding interaction between the factors single/dual-object, univalent/bivalent, and no-switch/switch was highly reliable, $F(1,15) = 18.1$, $P < 0.01$. This effect was not further modulated by the CSI, $F(1,15) < 0.8$, suggesting that it is not sensitive to preparatory activity. On the level of RTs, there seemed to be a tendency for a reverse pattern of effects with smaller switch costs in the single-object, bivalent condition, $F(1,15) = 3.9$, $P = 0.07$.[1] There was a general effect of CSI on RTs, $F(1,15) = 19.8$, $P < 0.01$, as well as an interaction with the switch factor, $F(1,15) = 6.3$, $P < 0.05$, but no further modulations of effects associated with the single/dual-object factor, all $Fs(1,15) < 0.8$.

To assess global selection costs in a way that is not confounded with local switch costs, we need to look at no-switch trials only. Here, we found a substantial increase in global costs (defined in terms of the difference between bivalent and univalent conditions) in the single-object condition (135 ms) over the dual-object condition (59 ms), $F(1,15) = 11.0$, $P < 0.01$. Again, this effect was not modulated by CSI, $F(1,15) < 0.8$. No corresponding difference in global costs was observed for errors, $F(1,15) < 0.6$.

Response-congruency effects can be computed for bivalent stimuli only. There was no reliable congruency main effect, $F(1,15) = 2.33$, $P < 0.15$, however, there was a reliable interaction with the single/dual-object factor, $F(1,15) = 5.48$, $P < 0.05$. As shown in Fig. 3, there was a considerable congruency effect in the single-object condition, $F(1,15) = 5.13$, $P < 0.05$, whereas this effect was all but eliminated for the dual-object condition, $F(1,15) < 0.4$. For error effects, we found a reliable interaction between single/dual object, switch, and congruency, $F(1,15) = 6.78$, $P < 0.05$. In the single-object condition, the error switch cost was 8.0% for the incongruent trials, whereas it was only 2.0% for congruent trials. The corresponding values for the dual-object condition were 1.8 and 2.0%. As this result suggests, the increased error switch cost in the single-object condition shown in Fig. 2 was exclusively due to incongruent trials. A plausible interpretation of this pattern is that the single-object condition induces a relatively high frequency of

Table 1 Mean RTs (SD) and error percentages (SD) as a function of the single versus dual object factor, the univalent versus bivalent factor, the CSI factor, and the switch factor

	Single object		Dual object	
	No switch	Switch	No switch	Switch
RT				
Univalent				
Short CSI	658 (132)	731 (129)	713 (146)	768 (140)
Long CSI	616 (151)	671 (165)	654 (178)	680 (183)
Bivalent				
Short CSI	812 (180)	891 (174)	781 (159)	876 (174)
Long CSI	730 (184)	771 (234)	706 (217)	760 (225)
Errors				
Univalent				
Short CSI	2.6 (5.0)	4.2 (4.4)	2.8 (3.9)	4.3 (4.0)
Long CSI	2.2 (3.1)	4.1 (5.4)	1.2 (1.5)	3.2 (2.7)
Bivalent				
Short CSI	4.3 (3.6)	10.2 (8.2)	5.4 (4.9)	5.7 (5.8)
Long CSI	3.3 (3.8)	7.3 (4.1)	3.5 (2.6)	3.8 (3.1)

[1]While this effect might suggest a speed-accuracy tradeoff, the critical error effect remained reliable, $F(1,9) = 5.3$, $P < 0.05$, after dropping six subjects with the largest reversed RT interaction (resulting in a near-zero RT interaction of 2 ms). Also, Table 1 indicates that the RT effect is mainly due to switch cost differences between the dual-object univalent and single-object univalent conditions. When the RT effect was analyzed for the bivalent condition alone, the relevant interaction was no longer present, $F(1,15) = 0.7$, $P > 0.4$, but still highly reliable for errors, $F(1,15) = 10.7$, $P < 0.01$. The larger RT switch cost in the univalent, dual-object condition may reflect increased demands of switching response locations that may be particularly pronounced in the overall faster univalent trials.

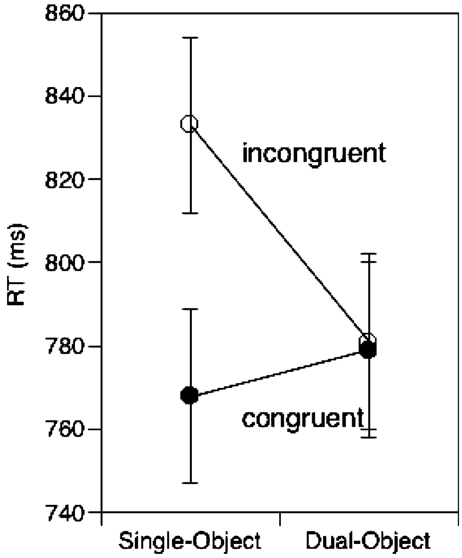


Fig. 3 Response times as a function of response congruency and the single-object versus dual-object factor. *Error bars* represent the 95% within-subject confidence intervals for the interaction between these two factors (Loftus & Masson, 1994)

failures to switch, which in the incongruent condition, should lead to incorrect, but fast RTs (because of the absent switch activity). Consistent with this assumption, incorrect responses were 110 ms faster than correct responses in this condition, $t(15) = 3.18$, $P < 0.001$. The corresponding effect in the dual-object condition was only 29 ms, $t(15) = 0.73$, $P > 0.4$.

As a final phenomenon, we turn to the interaction between the switch and the response-repetition factor. As mentioned in the Introduction, this effect seems to be linked to the trial-to-trial integration between codes involved in a particular selection instance (e.g., Hommel, 2004; Mayr & Bryck, 2005; Schuch & Koch, 2004) and, therefore, it is interesting to examine to what degree it is affected by the single/dual-object manipulation. As shown in Fig. 4, both for RTs and errors, the typical pattern with repetition benefits for task repetitions and costs for task changes was found in the single-object condition, but not in the dual-object condition. Here, benefits were obtained both for task repetitions and changes, even though these were reliable only for RTs in the task-repetition condition. The critical three-way interactions involving the factors single/dual object, switch, and response-repetition were reliable, RT: $F(1,15) = 9.95$, $P < 0.01$, errors: $F(1,15) = 6.73$, $P < 0.05$. No other higher order interactions involving either the ambiguity or the CSI factor were reliable, all Fs < 2.0.

Discussion

We show here that four important task-switching phenomena are affected by whether or not competing tasks use identical or distinct stimulus/response locations (single-object vs. dual-object condition). First, error switch costs were substantial in the single-object condition, but completely disappeared in the dual-object condition. Presumably, applying a task set to a particular stimulus/response object forms an association between the task set and that object. In the case of a task switch, this association keeps the last used task active and thereby increases the tendency to perseverate. In support of this interpretation, we found that error RTs in the single-object condition were very fast, suggesting that subjects simply failed to switch on these trials. Surprisingly, RT switch costs, which traditionally are the most prominent task-switching indicator, seemed least affected by the single/dual-object manipulation. It is possible that the use of two different sets of response locations may have increased response-execution demands, specifically for switch transitions. Thus, effects on the level of motor switch costs may have counteracted effects on the level of "true" switch costs.

As a second result, global costs, the increase of RTs experienced due to task-set competition on no-switch trials, were about twice as large for the single-object as for the dual-object condition. Global costs likely reflect the need to resolve stimulus-induced task-set competition (e.g., Mayr, 2001). When multiple tasks share stimulus/response parameters, activation of the lower level stimulus and response representations should lead to automatic activation of all associated task sets and

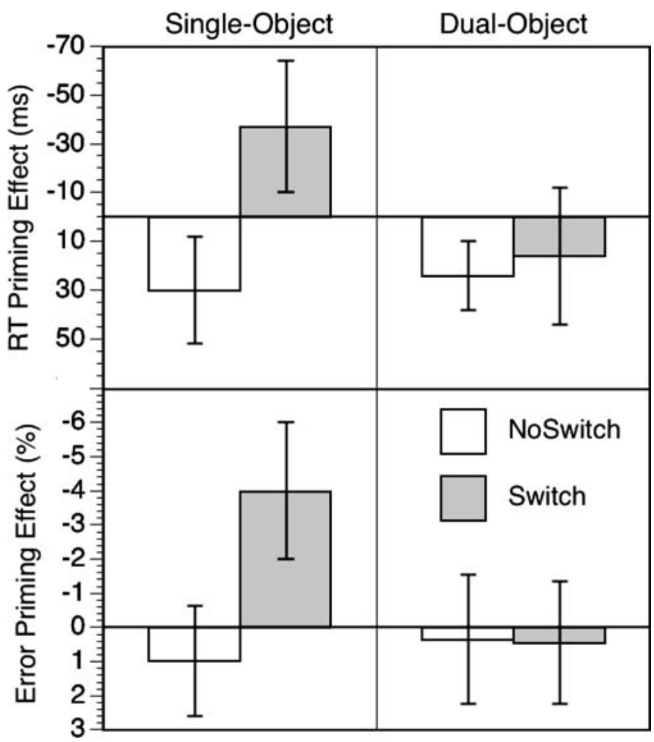


Fig. 4 Response times and error priming effects as a function of the switch factor and the single-object versus dual-object factor. *Error bars* represent the 95% within-subject confidence intervals for each individual difference score (Loftus & Masson, 1994)

thus increase the time it takes to resolve task-set competition. This effect of low-level overlap on global costs is broadly consistent with the result of Mayr (2001) who found that when response keys were shared across tasks, old adults showed much increased global costs.

Response-congruency effects reflect the degree to which response tendencies from the currently irrelevant task can infiltrate response selection on the currently relevant task. They are a standard and very robust phenomenon in basically all known task-switching experiments. A response-congruency effect in the usual magnitude was also obtained in the single-object condition. However, this effect disappeared completely in the dual-object condition, even though the stimulus features from both task dimensions were present in each of the two objects. Again, we believe the separate objects or locations permitted the creation of distinct task representations. These may either involve distinct filter settings associated with each location (e.g., Awh, Sgarlata, & Kliestik, 2004) or direct associations between critical stimulus values and specific physical response locations (e.g., green vs. red would not be coded in terms of left vs. right, but in terms of the left box within the left object vs. the right box within the left object).

A related result is that the response-repetition cost typically found for task-switch transitions was obtained for the single-object condition, but not for the dual-object condition. This type of repetition-priming pattern has been referred to as partial-overlap cost and has been directly linked to the establishment of integrated representations of all relevant parameters involved in a particular selection instance (e.g., Hommel, 2004, 2005). As a result of integration, it should be easy to either reuse the entire "package" or abandon it completely, but hard when individual features need to be "extracted" and reused in a different context (i.e., the situation of partial overlap). The fact that no such pattern was obtained when moving between objects/locations, again suggests that such integrated representations can become differentiated in terms of low-level physical properties (i.e., location).

None of the observed effects was modulated by how much time subjects had to prepare prior to each stimulus (i.e., the CSI). Assuming that preparation involves activating task-relevant representations in working memory, this result suggests that the codes that interact with the single/dual-object manipulation are not contained in working memory. Rather, this pattern is consistent with the idea that representations that integrate all relevant aspects of a selection episode are encoded into LTM and are automatically retrieved in case prominent features (such as the targeted location/object) are repeated in the next trial. The question how integrated event codes are related to preparatory activity clearly deserves further scrutiny. Interestingly, Wenke, Gaschler, and Nattkemper (2005) found evidence that such integrated episodes can arise through mere preparation for an upcoming task. However, it is an open question whether it is possible to create situations in which people can also "unbind" an existing and potentially interfering association in a proactive manner. For example, one might speculate that presentation of a stimulus that indicates the upcoming stimulus location (i.e., an exogenous location cue) during the preparatory interval may allow a proactive "remapping" between the lower level location representation and the task-set code.

From the perspective of research on task switching, an important conclusion from this set of results is that interactions between low- and task-level representations play a major role in the emergence of task-switching phenomena as we currently know them. Thus, task-switching researchers need to be aware of the fact that switch costs and other related effects are highly context dependent and should not be used in terms of chronometric assessments of the absolute duration of certain control operations. Likewise, researchers need to be very careful in generalizing their results to "real-world switching situations", where high degrees of low-level overlap are relatively rare. Having said that, we do not believe that this necessarily discredits the use of the task-switching paradigm. In fact, if carefully applied, it can be an excellent tool to study executive control processes in their intricate relationship with learning and memory processes (e.g., Mayr & Bryck, 2005; Waszak et al., 2003). Also, while low-level overlap is relatively rare in the natural world, these situations do arise and arguably these are exactly the situations with particularly high control demands. To name just one, perhaps less obvious, example: complex social situations often require approaching one and the same individual in terms of different roles (e.g., as a friend and as a co-worker, perhaps competing for some limited resource), each requiring different responses to similar stimuli. In other words, by understanding how the cognitive system deals with the consequences of low-level overlap, we may be learning something about its behavior in a rare, but relatively important type of situation.

On a more specific level, the conclusion that low-level overlap strongly contributes to certain task-switching phenomena, largely corroborates a suspicion expressed by Waszak et al. in discussing their finding of large stimulus-induced priming effects on switch costs. Specifically, they had speculated that costs not accounted for by specific stimulus repetitions might be due to other features that are shared across tasks, such as stimulus type or location. A novel aspect in our results is that the location or object a task is associated with may be particularly powerful in constraining carryover of representations across trials. At least the response congruency and the repetition-priming effects were completely eliminated in the dual-object condition. Functionally, a privileged role for objects/locations in constraining action-relevant representations makes sense given the fact that certain types of actions are usually tied to certain objects or locations. The integration-related effects we have observed are probably reflective of the same types of learning processes that, with experience, allow tools to become powerful triggers of action-relevant representations (e.g., Creem & Proffitt, 2001).

Open issues

Even in the current setup, one could argue that there was some degree of low-level overlap across tasks. For example, the use of identical objects across tasks could give rise to the impression that the same object ''jumps'' between locations. It will be important to see whether remaining task selection effects (i.e., in global costs and RT switch costs) can be eliminated in situations that provide even stronger bottom-up support for non-overlapping task-set representations.

The main goal of this research was to examine the impact of the typical way of doing task-switching experiments relative to the more natural way in which tasks are usually uniquely associated with objects in the world. This goal led to a design in which stimulus and response features were integrated within the same object, which precluded independent manipulation of the overlap of these features. Thus, currently, we cannot say to what degree stimulus overlap and response overlap play independent roles. Also, integration of both types of features itself may affect performance in ways that we cannot determine within the present design. Another aspect that was confounded in our work was objects and locations. Thus, we cannot say which of the two provide the critical constraints for carryover effects. All of these questions, however, should be addressable with variants of the present paradigm.

From an adaptive control perspective, a final important question is whether distinct representations for the two locations/objects arise in a mandatory manner. The alternative possibility is that this differentiation is the result of an adaptation to specific control requirements. In other words, codes associated with the left object and codes associated with the right object may be represented as distinct precisely because this allows eliminating between-task competition. With regard to the partial-overlap repetition-priming pattern, this leads to an easily testable prediction: in situations in which tasks never compete (e.g., when stimuli are univalent through the entire experiment), we should see the typical partial-overlap cost even across objects/locations.

To conclude, we show that core task-switching phenomena may arise at least in part, because of shared stimulus/response properties across tasks. We propose that these effects indicate a process of integration between low- and high-level codes, which serves an important function in a world in which often objects/locations are uniquely associated with specific tasks. If this view is correct, many task-switching ''costs'' are the consequence of placing a generally adaptive learning device in an ''unnatural'' situation where what is learned in one trial leads may be maladaptive in the next trial. For theoretical models of task switching, the current findings imply that both short-term (i.e., trial-to-trial) and also longer term learning mechanisms (see Waszak et al. 2003) need to be an integral part of any complete explanation of task-switching phenomena.

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References

Allport, D. A., Styles, E. A., & Hsieh, S. (1994). Switching intentional set: Exploring the dynamic control of tasks. In C. Umilta, & M. Moscovitch (Eds.), *Attention and performance XV*, (pp. 421–452). Hillsdale: Erlbaum.

Awh, E., Sgarlata, A. M., Kliestik, J. (2005). Resolving visual interference during covert spatial orienting: Online attentional control through static records of prior visual experience. *Journal of Experimental Psychology: General, 134* (2), 192–206.

Bryck, R. L., Mayr, U. (2005). On the role of verbalization during task-set selection: Switching or serial order control? *Memory and Cognition 33* (4), 611–623

Creem, S. H., & Proffitt, D. R. (2001). Grasping objects by their handles: A necessary interaction between cognition and action. *Journal of Experimental Psychology: Human Perception and Performance, 27*, 218–228.

Hommel, B. (2005). Feature integration across perception and action: Event files affect response choice. *Psychological Research*. This issue

Hommel, B. (2004). Event files: Feature binding in and across perception and action. *Trends in Cognitive Sciences, 8*, 494–500.

Jersild, A. T. (1927). Mental set and shift. *Archives of Psychology*, Whole No. 89.

Loftus, G. R., & Masson, M. E. J. (1994). Using confidence intervals in within-subject designs. *Psychonomic Bulletin and Review, 4*, 476–490.

Logan, G. D. (1988). Toward an instance theory of automatization. *Psychological Review, 95*, 492–527.

Marczinski, C. A., Milliken, B., & Nelson, S. (2003). Aging and repetition effects: Separate specific and nonspecific influences. *Psychology and Aging, 18*, 780–790.

Mayr, U. (2001). Age differences in the selection of mental sets: The role of inhibition, stimulus ambiguity, and response-set overlap. *Psychology and Aging, 16*, 96–109.

Mayr, U., & Bryck, R. B. (2005). Sticky rules: Integration between abstract rules and specific actions. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 31* (2), 337–350.

Mayr, U., & Keele, S. (2000). Changing internal constraints on action: The role of backward inhibition. *Journal of Experimental Psychology: General, 129*, 4–26.

Mayr. U., & Kliegl, R. (2003). Differential effects of cue changes and task changes on task-set selection costs. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 29*, 362–372.

Meiran, N. (1996). Reconfiguration of processing mode prior to task performance. *Journal of Experimental Psychology: Learning, Memory and Cognition, 22*, 1423–1442.

Meiran, N. (2000). Reconfiguration of stimulus task-sets and response task-sets during task-switching. In S. Monsell, & J. Driver (Eds.), *Control of cognitive processes: Attention and performance XVIII*. Cambridge: MIT Press.

Monsell, S. (2003) Task switching. *Trends in Cognitive Sciences, 7*, 134–140.

Rogers, R. D., & Monsell, S. (1995). The cost of a predictable switch between simple cognitive tasks. *Journal of Experimental Psychology: General, 124*, 207–231.

Rosenbaum, D. A., Kenny, S., & Derr, M. A. (1983). Hierarchical control of rapid movement sequences. *Journal of Experimental Psychology: Human Perception and Performance, 9*, 86–102.

Schuch, S., & Koch, I. (2004). The costs of changing the representation of action: Response repetition and response–response compatibility in dual tasks. *Journal of Experimental Psychology: Human Perception and Performance, 30*, 566–582

Spector, A., & Biederman, I. (1976). Mental set and mental shift revisited. *American Journal of Psychology, 89*, 669–679.

Waszak, F., Hommel, B., & Allport, A. (2003). Task-switching and long-term priming: Role of episodic stimulus-task bindings in task-shift costs. *Cognitive Psychology, 46*, 361–413.

Wenke, D., Gaschler R., & Nattkemper, D. (2005). Instruction-induced feature binding. *Psychological Research*. This issue