THE QUARTERLY JOURNAL OF EXPERIMENTAL PSYCHOLOGY
2010, 63 (4), 784–804

Psychology Press
Taylor & Francis Group

Selection of objects and tasks in working memory

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When people hold several objects (such as digits or words) in working memory and select one for processing, switching to a new object takes longer than selecting the same object as that on the preceding processing step. Similarly, selecting a new task incurs task- switching costs. This work investigates the selection of objects and of tasks in working memory using a combination of object-switching and task-switching paradigms. Participants used spatial cues to select one digit held in working memory and colour cues to select one task (addition or subtraction) to apply to it. Across four experiments the mapping between objects and their cues and the mapping between tasks and their cues were varied orthogonally. When mappings varied from trial to trial for both objects and tasks, switch costs for objects and tasks were additive, as predicted by sequential selection or resource sharing. When at least one mapping was constant across trials, allowing learning of long-term associations, switch costs were underadditive, as predicted by partially parallel selection. The number of objects in working memory affected object-switch costs but not task-switch costs, counter to the notion of a general resource of executive attention.

Keywords: Working memory; Executive control; Object switching; Task switching; Interference; Retrieval; Memory load.

Even very simple actions, such as grasping an apple or pressing a button, require at least two selection processes: the selection of an object (e.g., selecting the apple rather than the banana) and the selection of an action to apply to it (e.g., choosing to grasp rather than to smash the object). Both functions of selection have been extensively studied. Selecting the objects of action is the topic of research on selective attention, whereas selecting the action to be conducted in response to a stimulus is the topic of research on action control (for a review of both literatures, see Pashler, 1998). Selective attention has so far been studied mostly as attention to objects or stimuli perceptually present in the environment (Pashler, 1998; for exceptions see Lepsien & Nobre, 2006; Wager, Jonides, & Smith, 2006). Likewise, research on action control typically investigates simple overt actions (or "reactions") in response to perceived stimuli (e.g., Pashler, 1994; Rogers & Monsell, 1995). The

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This work was supported by Grant OB 121/3–3 from Deutsche Forschungsgemeinschaft (DFG).

http://www.psypress.com/qjep
DOI:10.1080/17470210903147486

same selection processes, however, also apply to trains of thought carried out in the absence of any direct environmental input and without overt response. For instance, in mental arithmetic we select representations of the objects of manipulation (i.e., the next digits to be processed) and the cognitive operation to perform on them (i.e., whether to add or subtract or multiply them, etc.). In such cases, both selection of the object of a (cognitive) action and selection of the action itself involve selection of representations in memory. This is advantageous for our purpose because it makes the targets of selection comparable: Rather than comparing selection of perceptual stimuli to selection of overt responses, we can compare selections of memory representations with different contents.

In this article we investigate how these two basic selection processes, which together determine the course of our thoughts and actions, are related to each other. Specifically, we address the following questions: First, are objects and the actions to be performed on them represented separately or as integrated units? To foreshadow, our answer will be that objects and actions are represented separately, and therefore our second question is: Are objects and actions selected independently and in parallel without mutual interference, or is there a capacity limitation applying to both selection processes, so that they have to proceed sequentially? Our third question is whether either or both selection processes are limited by the capacity of working memory. Finally, we ask whether the limitations on both selection processes, and their interaction, is modulated by whether selection is based on temporary bindings in working memory, or more permanent associations in long-term memory. In the following we first introduce our theoretical framework, followed by an introduction to the switching paradigms combined in our experiments, and then we elaborate the theoretical context of each question in turn.

Selection of representations in memory

The selection of relevant representations for cognitive or overt action is commonly regarded as one of the main functions of working memory (e.g., Baddeley, 1986; Cowan, 1995, 2001). We use as the theoretical framework for the present study a theory of working memory (WM) that puts selection of representations at centre stage (Oberauer, 2002, 2006). The theory distinguishes three embedded components of WM, which are best understood as three states of representations as they become selected for processing.

On the first level of selection, representations in long-term memory (LTM) are activated. The set of representations activated above baseline creates the first, most encompassing component of WM, called the *activated part of long-term memory* (cf. Cowan, 1995). On the second level of selection, a subset of activated representations becomes bound by temporary bindings to representations of their current context, such as their location in space, or their serial position in a list. These representations constitute the second component of WM, called the *region of direct access*. Representations in the region of direct access are directly accessible for processing through their current contexts—that is, the contexts act as retrieval cues for the contents bound to them. For instance, if a list of three words is to be remembered in order, they can be bound to representations of the first, second, and third position, respectively. When asked to access the second word as input to a cognitive operation—for example, to decide whether it refers to a living thing—then that word can be accessed directly by focusing on the requested position as a context cue and retrieving the word bound to it. Focusing on one particular element's context, and retrieving the one element bound to it, brings into play the third component of WM, the *focus of attention*. Thus, the third level of selection is for a representation to actually be accessed and thus recruited for a cognitive operation—that is, being brought into the focus of attention. The focus holds at each time one element together with the context it is bound to and thereby selects this representation as the object of the next cognitive operation.

As developed so far, this theoretical framework has been concerned only with selecting the input to cognitive processes—that is, the representations of objects such as words or digits that can then be manipulated through cognitive operations (e.g., classified or counted). Little attention has been given to the representations of the operations themselves—that is, the tasks and their corresponding rules to be performed with these objects. The goal of the present research is to bring the "working" part of WM more explicitly into the picture by investigating the representation and the selection of both objects and tasks in WM in a common experimental and theoretical framework (for a more thorough theoretical elaboration, see Oberauer, in press).

Selection of actions can often be broken down into two choices on two levels: First, the person has to choose an action goal and then the corresponding rules of how to respond to possible objects. For example, the person could choose to sort apples by their size, using the rule that the large ones go into the left crate, and the small ones go into the right crate. Alternatively, the person could sort the apples by colour, putting the red ones in the left crate and the green ones into the right crate. The choice of a task that implements the action goal must precede the choice on the second level, the selection of the actual action in response to each object. For instance, once the decision has been made to sort by size, the task representation determines that a small red apple must be placed into the right crate. In this article, we focus on the first level of selection for action control: the selection of a task.

Object switching and task switching

Switching paradigms provides a useful experimental methodology to investigate object and task selection processes. Switching between objects in WM was first investigated by Garavan (1998) who asked participants to update two counters, one for each of two kinds of geometrical figures. The counters were updated in response to geometrical figures displayed one by one, with each new figure either demanding an update of the same counter as in the preceding step or switching to the other counter. Switching between counters incurred a cost of about 300 ms, which Garavan interpreted as the time to switch the focus of attention in WM to a new mental object. Later research has further investigated these *object-switch costs* in WM with arithmetic tasks (e.g., Oberauer 2002, 2003). Participants remembered a memory set of between two and four digits and applied arithmetic operations (e.g., $+3$ or -4) presented on the computer screen to selected digits from the memory set. The digits were distinguished by their spatial positions on the screen when they were initially presented. Each arithmetic operation was displayed in one of these positions, thereby indicating to which digit it was to be applied. In this way, for each operation one digit in WM had to be selected and processed while the currently irrelevant digits had to be remembered and kept accessible for later processing steps. These experiments showed again costs of switching to a new object in WM, and these costs increased with memory set size.

Selection of tasks has been studied with the task-switching paradigm (e.g., Meiran, 1996; Rogers & Monsell, 1995). In classic studies, participants were instructed to report the results of arithmetic equations in which the digits were displayed without the operation signs, and either participants had to solve a set of equations by using the same operation (addition or subtraction) throughout, or they had to mentally switch with each new equation between addition and subtraction (Jersild, 1927; Monsell, 2003; Spector & Biederman, 1976; for an example of more recent research with arithmetic equations, see Baddeley, Chincotta, & Adlam, 2001).

The basic finding in the task-switching paradigm is the same as that in the object-switching paradigm: Task repetitions are performed faster than task switches, resulting in reliable switch costs. Nonetheless, despite the similarity in design and results, and the fact that both paradigms have been used, among others, with arithmetic operations to obtain insight in the respective switching processes, there is not much research trying to relate object switching and task switching.

The lack of integration of the two literatures might in part be due to differing theoretical interpretations for the observed switching costs. Object-switching costs have been primarily interpreted as evidence for a focus of attention in WM that can hold only one element at a time (Garavan, 1998; Oberauer, 2002, 2003). Task-switching costs have been mostly discussed as reflecting additional executive control processes responsible for selecting the currently relevant task in the presence of temporarily irrelevant competitors (Logan, 2004; Mayr & Kliegl, 2000, 2003; Meiran, 1996; Rogers & Monsell, 1995). We believe this is a difference more in emphasis than in substance. First, if executive control is defined as any process that controls the content and direction of cognitive activity in the presence of competing alternatives, the selection of a new object in WM can likewise be called an instance of executive control (as done by Garavan, Ross, Li, & Stein, 2000). Second, both kinds of switching require a way of representing the selected object or task that sets it apart from other, not selected alternatives. The notion of a focus of attention in WM refers to a mechanism for maintaining the representation of one object in a privileged state. Likewise, selection of one task to guide action implies that the selected task has a special representational status that sets it apart from other tasks. For instance, Monsell (2003) proposes that the currently selected task is held in "procedural working memory" (cf. Oberauer, in press). Third, theorists in both research traditions have described this selection process as cue-based retrieval. In task switching, an externally presented or internally generated cue (e.g., the word "addition") serves to retrieve a representation of the task itself (Logan, 2004; Mayr & Kliegl, 2003). In object switching, the geometric figure (Garavan, 1998) or the spatial position of the arithmetic operation (Oberauer, 2003) serves as the cue for retrieving the relevant object in WM.

To investigate the relation between object selection and task selection we conducted four experiments with an arithmetic WM task (Oberauer, 2003) that required selection of objects as well as selection of tasks. In each trial participants remembered sets of two or four digits, each associated to a different location on the computer screen indicated by spatially arranged frames. A series of arithmetic operations was to be applied to individual digits. Each step in the series involved adding or subtracting a new digit, displayed on the screen, to one of the digits held in memory, and to type the result as quickly as possible. In each step, the participants had to select both the correct digit from the memory set and the correct arithmetic operation (i.e., addition or subtraction). Selection was guided by two cues. The digit to be selected was indicated by the frame in which the new digit was displayed, whereas the arithmetic operation was indicated by the colour to which the frame changed simultaneously with the display of the new digit (see Figure 1 for an example). Importantly, from one step to the next the to-be-selected object could be repeated or switched, and the arithmetic operation could be repeated or switched. Crossing the two switching variables results in the following conditions: repetition of both object and task, object repetition with task switch, object switch with task repetition, and switch of both object and task.

Research questions and predictions

Integrated or separate representations?

A first question to be addressed is whether selected objects and tasks are represented as separate units in WM. One possibility is that objects and tasks are integrated into unitary representations that are selected as one. This view can be motivated by the theory of event coding (Hommel, Müsseler, Aschersleben, & Prinz, 2001), according to which stimuli and the actions applied to them are represented as composites. Research with the task-switching paradigm has shown that stimuli, when repeated in a sequence of trials, act as automatic retrieval cues for the task applied to them before (Waszak, Hommel, & Allport, 2003). Thus, there is evidence that tasks are not selected completely independent of the objects they were applied to, and objects are associated to the tasks applied to them. A strong version of the theory of event coding would imply that unified *event files*, rather than separate object and task representations, are the units of selection. In this view, the selected object and the selected task are fused into a joint representation. Thus, there would be a single selection mechanism, such as the focus of attention in WM,

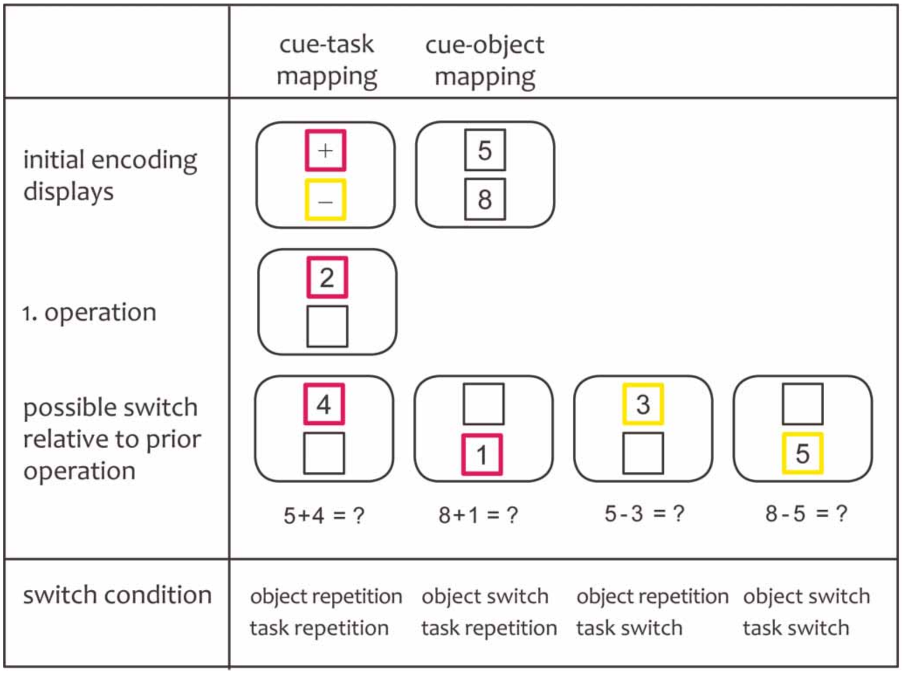

Figure 1. *Example of the four switch conditions relative to a given first operation realized in a trial with two objects. In the upper row, the initial encoding displays for both the cue–task and the cue–object mapping are illustrated. The arithmetic equations below the possible second operation depict the mental operation to be calculated in each example. The result of each equation would have to be typed in via a keyboard. To view a colour version of this figure, please see the online issue of the Journal.*

which holds an event file that integrates an object and a task. As a consequence, selection of a new object implies deselecting the old task, and, likewise, selection of a new task implies that the last used object has to leave the focus of attention. This view predicts that switching the object abolishes the benefit of repeating the task, and switching the task abolishes the benefit of repeating the object. This prediction implies an underadditive interaction of object switching and task switching rather than additive effects, but with the strong constraint that only the condition in which both object and task are repeated is completed faster than the other three conditions, which should not differ. This pattern of interaction is shown in the left panel of Figure 2.

Parallel or serial selection?

If objects and tasks are represented separately, selecting each of them is a separate process, and we can ask whether these processes can proceed independently of each other in parallel, or whether they compete for a common mechanism or a common resource, such that they cannot be carried out simultaneously without mutual interference. A common mechanism can be conceptualized as a processing bottleneck that permits only one selection process at a time (Pashler, 1994). This view has plausibility because both object selection and task selection involve retrieval, and retrieval from LTM seems to be constrained by a bottleneck, such that only one representation can be retrieved at any time (Maylor, Chater, & Jones, 2001; Rickard & Bajic, 2004). Mayr and Kliegl (2000) provide direct evidence that task selection interferes with retrieval from episodic LTM. It is equally plausible to assume that the same constraint also applies to retrieval from WM. On this view, we would expect a bottleneck for the two selection processes. Thus, when

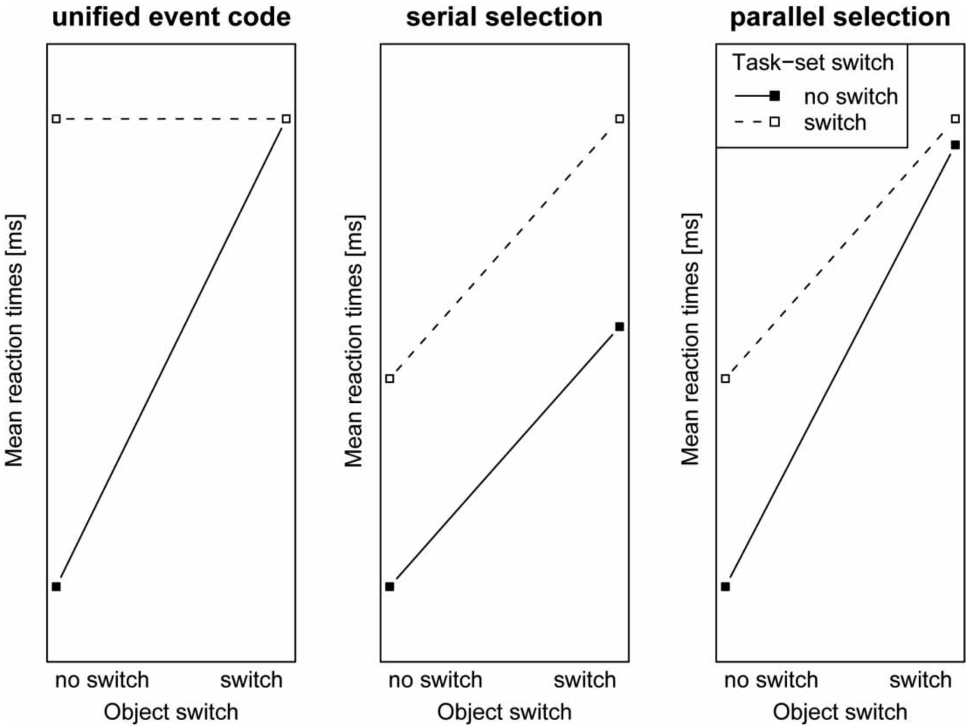

Figure 2. *Schematic illustration of the expected interactions between object and task switching conditional on three different hypotheses regarding the selection mechanisms. The left panel illustrates selection from the perspective of unified event codes, the right panel depicts the outcome with parallel selection, and the middle shows serial selection.*

selection of a new object and a new task are required at the same time—as in the double-switch condition of our experiments—the two selection processes must run sequentially. As a consequence, the time costs for object switching and for task switching should be additive, as illustrated in the middle panel of Figure 2.

A somewhat different conceptualization is to assume separate mechanisms that are controlled by the same resource. Some theorists assume a unitary resource for executive attention (Kane & Engle, 2002; Lavie, Hirst, de Fockert, & Viding, 2004). Because object selection and task selection can both be regarded as instances of executive control, these theories should predict that the two selection processes compete for the same limited resource of executive attention. Resource theories are more flexible than bottleneck theories in that they permit parallel execution of two processes that compete for the same resource. Resource sharing, however, comes at the cost of slowed processing. Two equivalent formalizations of resource sharing (Navon & Miller, 2002; Tombu & Jolicoeur, 2003) assume that processing speed is reduced in direct proportion to the reduction of resources assigned to a process. For instance, if both processes are assigned 50% of the available resources, both would take twice as long to complete, compared to when they received 100% of resources. As a consequence, the time for completing both processes is the sum of the completion time for each process, conducted on its own. This is the same prediction as that resulting from the bottleneck assumption. In terms of our design, object and task switching should affect reaction times (RTs) additively.

The alternative view to shared selection mechanisms or resources is that task selection and object selection are accomplished by separate and independent mechanisms. This implies that they can proceed in parallel without mutual interference. As a consequence, the completion time for both selection processes together would be substantially less than the sum of their individual durations (cf. Göthe, Oberauer, & Kliegl, 2007; Oberauer & Kliegl, 2004, for distinguishing serial and parallel processes in WM-updating tasks). The time for switching both object and task is the maximum of two random variables. The mean of that maximum is longer than the mean of the longer switch process individually (how much longer depends on the variance of both durations), but shorter than the sum of the means of both switching processes. Therefore, parallel selection would result in an underadditive interaction between object and task switching, as illustrated in the right panel of Figure 2. This interaction differs from the predictions of a unified event code in that there should still be repetition benefits of the object when the task is switched and repetition benefits for the task when the object is switched.

Are object selection and task selection limited by working memory capacity?

The third question motivating our research concerns the relationship between WM capacity and the two selection processes we investigate. One widely held view about WM capacity is that it reflects a limited resource for executive attention (Kane & Engle, 2002; Lavie et al., 2004). As argued above, both task selection and object selection can be regarded as instances of executive control requiring executive attention. Thus, the executive-attention view of WM capacity predicts that increasing WM load should impair both selection processes, leading to an increase of object-switch costs and task-switch costs. To test this prediction we varied the size of the set of digits from which one had to be selected for each arithmetic operation.

An alternative prediction is that the size of the digit set affects the time to select a new digit (i.e., object-switch costs), but not the time to select a new task (i.e., task-switch costs). This prediction can be motivated on two grounds. First, one could posit that there are separate resources for representing and selecting task sets on the one hand and for representing and selecting the objects of processing on the other hand, and increasing digit set size increases the load only on the latter. Second, one could dismiss the idea that maintenance and processing (including selection) compete for common resources. Rather, the time for selecting a representation can be assumed to reflect the time to resolve competition between candidates for selection, which increases as the set of candidates increases (Oberauer & Göthe, 2006). On this view, the time demand for selection of representations depends not on the number of all elements held in WM, but only on the number of potential candidates for selection. Thus, object selection time is affected by object set size because with larger sets, more digits compete for being selected into the focus of attention. Tasks, in contrast, would not compete for being selected as objects, and objects would not compete for being selected as tasks. In that case, the number of digits would have no effect on task-switch costs but exert a selective set-size effect on object switching only.

Retrieval from working memory or from long-term memory

When comparing object switching and task switching, we need to consider a further complicating factor. As noted above, both object and task selection processes can be viewed as cue-based retrieval. Therefore, selection can be expected to depend on the quality or strength of the link between the cue and its retrieval target.

In task-switching paradigms experimenters typically realize a fixed mapping of task cues to tasks, providing a strong link between cues and their target representations. In some experiments these links are already part of the participants' semantic memory before they start the experiment—for example, when the word "parity" is displayed to cue a parity judgement. In other experiments, arbitrary cues are mapped to tasks by an instruction at the beginning but then stay constant throughout the experiment. In object-switching studies, in contrast, the mapping between the retrieval cues and the objects linked to them are varied from trial to trial. For instance, Oberauer (2003) presented a new set of digits to be remembered on each trial, and each digit was linked to a spatial location (Experiment 1a) or to a colour (Experiment 1b). The spatial location or colour, respectively, served as a cue to retrieve the digit to which each arithmetic operation was to be applied.

The stability of the mappings between retrieval cues and retrieval targets is a potentially important difference between the two switching paradigms. A fixed mapping as typically used in the task-switching paradigm is likely to establish an association between task cues and tasks in LTM, whereas a varied mapping as used in the object-switch paradigm would not permit much reliance on LTM associations. Rather, participants would have to rely on temporary bindings between cues and objects that are rapidly updated from trial to trial. Maintaining and updating these temporary bindings is the function of WM, in particular the direct-access region. Indeed, we argue that what it means for a representation to be "in working memory" is just that it is linked to the relevant retrieval cue only by a temporary binding rather than by a long-term association (cf. Oberauer, 2005, 2007). Thus, we further manipulated the mapping assignments between objects and tasks and their retrieval cues, crossing varied and fixed cue−object and cue−task mappings between experiments. Our fourth research question is whether the findings with regard to the first three questions are modulated by whether objects or task sets are retrieved through temporary bindings in WM or through more permanent associations in LTM. One prediction to be motivated by the executive-attention view of WM, for instance, is that maintenance of digits in WM competes with only those selection processes that are based on bindings in WM, whereas selection from LTM is not limited by the executive resource assumed to fuel WM.

OVERVIEW OF EXPERIMENTS

We conducted four experiments that investigate the relation of object and task selection in a common approach on WM. In each experiment, both the tasks (i.e., addition and subtraction) and the objects to which they were applied (i.e., digits) had to be retrieved from memory. As a further manipulation within each experiment, the set size of the memory objects was varied between two and four digits. Between experiments, we orthogonally manipulated the mapping assignments between object and task representations and their corresponding cues. The first experiment represents the traditional implementation with varied mapping for objects and fixed mapping for tasks. In the second experiment, both objects and tasks had to be accessed via varied mappings, so that both objects and tasks are represented in WM. The third experiment was the mirror image of the first, using a fixed mapping for objects but a varied mapping for tasks. Finally, the fourth experiment used fixed mappings for both objects and tasks.

General method

Participants

A total of 80 students from a Potsdam high school were tested, with a different group of 20 participants participating in each of the four experiments described below. The participants' age ranged from 16−22 years across experiments with an average age of 18 ($SD = 0.66$), 18 ($SD = 0.83$), 18 ($SD = 1.61$), and 17 ($SD = 0.89$) years, respectively. In Experiment 1, 9 participants were male, and 11 were female. In Experiments 2 and 3, there were 8 males and 12 females participating in each experiment. In Experiment 4, we tested 3 males and 17 female participants. They received €12 for two 1-hour sessions.

Apparatus and stimuli

All experiments were performed using a 368 PC. The software was programmed with Turbo Pascal. Responses were recorded from a standard German QWERTZ keyboard using the number keys. The to-be-encoded set of digits was displayed by presenting either two or four white framed rectangles on a black background each containing a white digit that disappeared after self-paced encoding. In the condition with four digits the respective frames were equidistantly arranged around the virtual centre of the computer screen, on the left and right sides of the vertical middle axis as well as above and below the horizontal middle axis. In the condition with two digits only the two frames above and below the horizontal middle axis were displayed (as illustrated in Figure 1).

In the fixed-mapping condition, tasks were assigned to their respective cue colour by verbal instruction. In the varied mapping condition, no such instruction was given. Instead, an additional display was presented before encoding the digits showing the currently relevant cue–task mapping. This display contained two differently coloured frames above and below the horizontal middle axis with a "+" or "−" presented in the centre of each frame.

Procedure and design

Each experiment was performed in two 1-hour sessions, consisting each of four blocks with 25 trials, resulting in a total of 200 trials per participant. Half of the participants in each experiment started the first session with a block sequence of 2–4–2–4 objects and performed the reversed order in the second session. For the other half the sequence was reversed. Prior to each block participants were informed about the current object set size.

Each trial consisted of a self-paced encoding phase and an equally self-paced processing phase. The encoding procedure differed across experiments conditional on the cue–object and cue–task mapping condition and is thus described below in more detail. The procedure for the processing phase of each trial was identical in each experiment. After encoding, pressing the space bar initiated the first of nine operations. For each operation one rectangle was randomly selected by colouring its frame. The location of the coloured frame specified the relevant object (i.e., the digit to be used for the arithmetic operation) whereas the colour cued the relevant task (i.e., addition or subtraction). Simultaneously with the appearance of the colour cue, a white digit was displayed in the centre of the cued frame indicating that this value had to be added to or subtracted from the digit associated with this frame. The digits displayed were selected such that the results of the arithmetic operation ranged from 1 to 9. The result of each operation was entered on the computer keyboard, and this initiated the immediate presentation of the next operation. Acoustic feedback was provided after each response. Note that the result of each operation was entered without updating the memory list of digits. Latencies and accuracies of responses were collected for nine successive operations per trial. Participants were instructed to perform the arithmetic operations as quickly and accurately as possible and received a further feedback at the end of each block regarding the percentage of correct responses.

The procedure of encoding tasks and objects prior to each trial differed depending on the mapping condition. In the experiments with a fixed cue–task mapping, all participants were instructed prior to the experiment that a red frame indicated addition whereas a yellow frame indicated subtraction. In the varied cue–task mapping condition, an additional display was presented on each trial. This display contained the currently relevant cue–task mapping by presenting a "+" or "−" in the centre of two differently coloured frames above and below the horizontal axis. Two different cue colours were randomly selected from a pool of six colours (i.e., red, yellow, green, orange, blue, and brown); colours were not repeated in subsequent trials. In the varied cue–object mapping condition, at the beginning of each trial digits were randomly selected from numbers ranging from 1 to 9. In the fixed cue–object mapping condition, each participant worked on a fixed set of digits that was presented prior to each trial. In the condition with set size two, only the two digits associated with the frames above and below the horizontal middle axis were displayed.

Using the same set of objects throughout the whole experiment required two further changes to maximize the number of possible operations that would still result in values ranging from 1 to 9. First, we reduced the range of digits for the memory sets from 3 to 7. All possible combinations of four-object sets that can be constructed from the five remaining digits were permuted within a Latin square, resulting in 20 different sets with each of the five digits being equally often presented in each frame position. Each participant performed on one of these sets. Second, we restricted the range of possible digits to be displayed on the screen (i.e., the second digit in each equation) to digits from 1 to 4 (instead of 1 to 8 as in the experiments with varied cue–object mapping). This change was required to prevent the situation that participants working on a set of objects with higher values would on average have to add smaller digits than would participants working on a list of lower object values who likewise would have to subtract smaller numbers.

In summary, in Experiment 1 with fixed cue–task mapping and varied cue–object mapping, participants received a verbal instruction of the colour-to-task mapping (i.e., red for addition and yellow for subtraction) prior to the experiment. Each trial thus started with self-paced encoding of the objects with two or four different digits selected at random. After pressing the space bar, the nine operations were presented, each requiring an immediate response. In Experiment 2, with varied cue–task mapping and varied cue–object mapping, each trial started with displaying the relevant colour–task combinations. After pressing the space bar, the set of randomly selected digits was displayed to be encoded. Pressing the space bar again initiated the start of operations. In Experiment 3, the cue–task mapping varied across trials whereas the cue–object mapping was fixed. Thus, the first display in each trial showed the randomly selected cue colour for each task relevant in the upcoming trial. The second display showed the two or four digits in their frames that were the same throughout the experiment. In Experiment 4 both cue–task and cue–object mappings were fixed. As in Experiment 1, participants were to associate a red frame with the task addition and a yellow frame with subtraction by instruction at the beginning of each session. The fixed set of digits was presented on the computer prior to each trial (as in Experiment 3).

Classification of switch conditions and data trimming

By independently manipulating object and task switching (i.e., cue location and cue colour) four different switch conditions were realized with respect to the prior operation: repetition of both object and task, an object repetition with task switch, a task repetition with object switch, and switching both object and task. The first operation in each trial could not be classified as one of these switch conditions and was thus excluded from analyses. The remaining eight operations in each trial were equally distributed across the four different switch conditions. The first trial in each block was considered as practice, leaving 24 test trials per block. Each participant thus performed 1,536 responses in total with 192 data points per design cell.

We further refer to object-switch costs as the difference in mean RTs between the conditions in which the object was switched and those in which it was repeated, averaging across the task-switching factor (unless specified otherwise). Likewise, task-switch costs indicate the additional time when the task has to be switched compared to repeating the task, averaged across object-switching conditions.

For all analyses, we only considered RTs of correct responses. In a first step, outlier RTs smaller than 300 ms and larger than 10,000 ms were removed. For each participant, we further excluded RTs exceeding the individual's mean in each design cell by more than three intraindividual standard deviations, also calculated for each design cell. The final number of data points submitted to each analysis are reported in the Results section separately for each experiment.

Data analysis

Mean RTs were submitted to separate 2 (number of objects: 2 vs. 4) × 2 (object switching: no switch vs. switch) × 2 (task switching: no switch vs. switch) repeated measures analyses of variance (ANOVAs) for each experiment. Additional planned *t* tests (one-tailed) were performed to follow up predictions on the interaction between object switching and task switching.

EXPERIMENT 1

In the first experiment the interaction between object and task switching was examined using a varied cue–object and a fixed cue–task mapping, thereby reproducing the typical mappings in previous studies on object switching and task switching, respectively.

Results and discussion

Error correction and data trimming left 93% of data points for analyses. As can be seen in Figure 3, the main effects of both object switching and task switching were significant, $F(1, 19) = 40.5$, $MSE = 115{,}139$, $p < .001$, and $F(1, 19) = 14.1$, $MSE = 21{,}363$, $p = .001$, respectively. Most important for the present question, object switching and task switching interacted underadditively, $F(1, 19) = 5.2$, $MSE = 27{,}876$, $p = .034$. This interaction was in turn modulated by the number of objects, with $F(1, 19) = 11.8$, $MSE = 2{,}516$, $p = .003$, for the three-way interaction. The main effect of number of objects in the memory list was also significant, $F(1, 19) = 42.9$, $MSE = 27{,}287$, $p < .001$. Memory set size interacted with object switching, $F(1, 19) = 47.5$, $MSE = 19{,}244$, $p < .001$, but not with task switching, $F(1, 19) < 1$, $MSE = 6{,}545$, $p = .983$. Object switch costs averaged across task switching increased from 190 ms with two objects to 493 ms with four objects. In contrast, task switch costs amounted to 87 ms for both two and four objects.

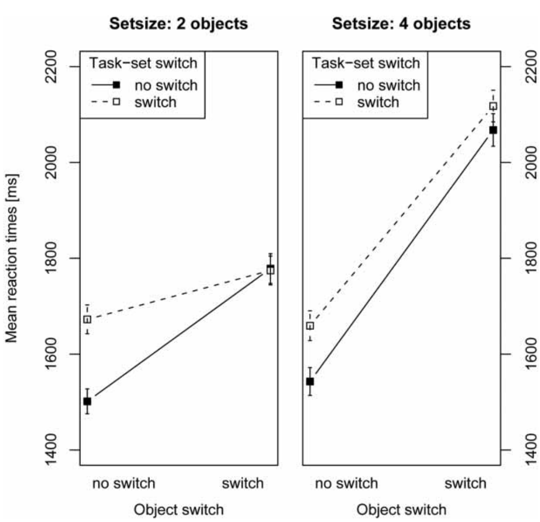

Figure 3. *Results of Experiment 1. The left panel shows reaction times with two objects; the right panel shows reaction times with four objects. Error bars are 95% confidence intervals.*

To evaluate whether the underadditive interaction reflects the pattern predicted by a unified "event code", with repetition benefits only when both object and task are repeated, we tested for object-switch costs in the presence of a task switch. Put differently, we tested whether there was a benefit for repeating the object although the task had to be switched relative to the double switch condition of both object and task. Paired *t* tests revealed that this was the case. There were object-repetition benefits of 103 ms with two objects, $t(19) = -2.03$, $p = .03$, and of 459 ms with four objects, $t(19) = -5.74$, $p < .001$. Thus, the pattern of interaction between object switching and task switching is more in line with the prediction of two selection processes running partially in parallel (right panel of Figure 2) than the prediction from the unified event code hypothesis (left panel of Figure 2).

To summarize, the results of Experiment 1 showed substantial switching costs for both object switching and task switching in a paradigm in which both objects and tasks are represented in memory. The switching variables interacted underadditively. The pattern of interaction did not match the prediction of objects and tasks being selected as a unified event code. Object repetition benefits were observed even when the task was switched, suggesting that tasks and objects can remain selected (or at least primed for selection) while the other is changed. The underadditive interaction rather indicates that a new task could be retrieved in parallel with a new object. This can be counted as first evidence that selection of objects and tasks do not compete for a common selection mechanism.

In addition, the number of objects selectively affected object-switching costs and not task-switching costs. Holding a larger number of digits in memory did not interfere with task switching, indicating that selecting a new task and maintaining objects in WM did not rely on the same executive resource. In this experiment, using a fixed cue–task mapping, this might have been the case because tasks were represented in LTM rather than in WM (see Mayr & Kliegl, 2000, 2003). The remaining experiments show, however, that the selective influence of object set size on object-switch costs but not task-switch costs was a general pattern.

EXPERIMENT 2

The second experiment was conducted to test whether stronger evidence for interference between object selection and task selection would be found when both objects and tasks must be held in WM. Thus, we replaced the fixed cue–task mapping of Experiment 1 by a varied mapping similar to that used for object selection. Analogous to the procedure of encoding the objects, the colour cues for each task changed with every trial. We expected that interference between the two selection processes was more likely in this experiment due to the fact that tasks should now be accessed, like objects, via temporary bindings from WM. Moreover, if WM capacity reflects a unitary resource for executive attention, both selection processes should be affected by increasing WM load from two to four objects.

Results and discussion

Elimination of error RTs and trimming left 92% of the data for analysis. Both object switching and task switching had significant main effects, $F(1, 19) = 108.4$, $MSE = 125{,}486$, $p < .001$, and $F(1, 19) = 64.1$, $MSE = 20{,}146$, $p < .001$, respectively. Figure 4 shows that object switching and task switching did not interact ($F < 1$). The three-way interaction was also not significant, $F(1, 19) = 2.1$, $MSE = 2{,}910$, $p = .167$. The main effect of number of objects was again significant, $F(1, 19) = 41.4$, $MSE = 29{,}335$, $p < .001$, and it interacted with object switching, $F(1, 19) = 21.9$, $MSE = 34{,}021$, $p < .001$, but not with task switching, $F(1, 19) < 1$, $MSE = 3{,}857$, $p = .477$. While object-switch costs increased from 447 ms with two objects to 720 ms with four objects, task switch costs even showed a small decrease from 187 ms to 173 ms with increasing number of objects.

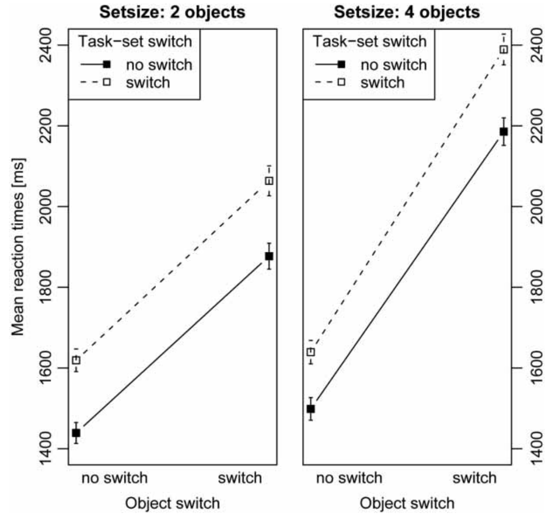

Figure 4. *Results of Experiment 2. The left panel shows reaction times with two objects; the right panel shows reaction times with four objects. Error bars are 95% confidence intervals.*

We found additive effects of object switching and task switching when both object and task had to be accessed in a varied cue–target mapping condition. This indicates that selecting a new object and task via temporary bindings depends on a common selection mechanism that functions like a selection bottleneck, or a common resource that slows both selection processes down to half their speed when executed in parallel (Navon & Miller, 2002; Tombu & Jolicoeur, 2003).

Nevertheless, there was still a selective effect of the number of objects on object switching but not on task switching. This finding is not compatible with the assumption that selection of representations and maintenance in WM share the same general executive resource. One alternative view discussed in the Introduction is that there are separate resources for maintaining and selecting objects (such as digits) in WM on the one hand and for maintaining and selecting task sets on the other hand. This view, however, conflicts with the conclusion that selecting objects and selecting task sets compete with each other so that they can be carried out only serially. Therefore, we prefer the remaining alternative hypothesis, which abandons the notion of resources shared between maintenance and selection processes. Instead, we submit that the object set-size effect on RTs reflects the time for resolving the conflict between competing representations in WM. Holding more objects in the region of direct access results in more competition for the selection of one object, but does not affect the competition for the selection of task sets. Therefore, increasing memory set size slows down selectively only the object selection process, not the task selection process.

EXPERIMENT 3

The previous experiment suggests that the set-size effect in WM is due to competition between representations competing for selection into the focus of attention, not to the need to share WM resources between storage and processing. Experiment 3 tests a further prediction resulting from this hypothesis: Object set size should affect object-switch costs (but not task-switch costs) even when the objects are mapped to their cues by a fixed mapping and therefore can be retrieved through associations in LTM. Even though objects are not maintained "in working memory", they still act as competitors for being selected. In contrast, on the assumption of a general executive resource in WM we should expect set-size effects only if the set-size manipulation increases the load on the limited capacity of WM.

In this experiment, the same set of four different digits was repeated throughout the whole experiment. In the condition with two digits, a constant subset of two out of the four digits was selected. The cue–task mapping was varied as in Experiment 2. Because the digits are all competitors for being selected as the input for the arithmetic operation, we still expected larger RTs and increasing object-switch costs with larger number of relevant objects.

Results and discussion

Figure 5 shows the results, based on 94% of the data points left after elimination of error RTs and trimming. The main effects of object switching and of task switching were again significant, $F(1, 19) = 100.8$, $MSE = 55{,}563$, $p < .001$, and $F(1, 19) = 42.6$, $MSE = 45{,}019$, $p < .001$, respectively. The interaction between object and task switching was significant, $F(1, 19) = 11.8$, $MSE = 8{,}381$, $p = .003$, but the three-way interaction was not, $F < 1$. The effect of number of objects also reached significance, $F(1, 19) = 12.9$, $MSE = 72{,}915$, $p = .002$, and it interacted with object switching, $F(1, 19) = 7.4$, $MSE = 10{,}623$, $p = .014$, but not with task switching, $F < 1$. Object-switch costs showed again a substantial increase from 330 ms with two objects to 419 ms with four objects. In contrast, task-switch costs did not differ with increasing number of objects (two objects, 218 ms; four objects, 220 ms).

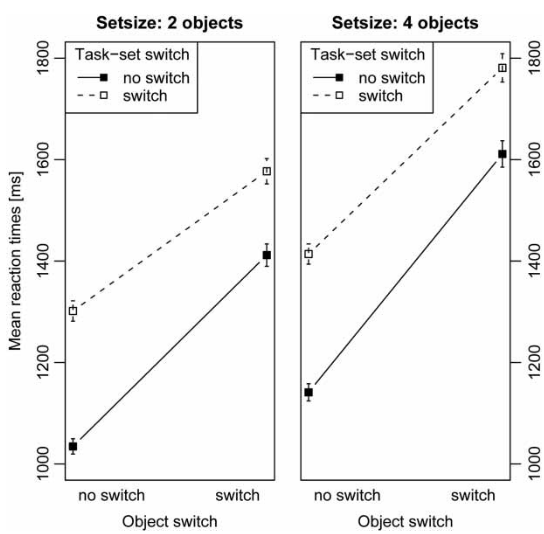

Figure 5. *Results of Experiment 3. The left panel shows reaction times with two objects; the right panel shows reaction times with four objects. Error bars are 95% confidence intervals.*

To qualify the underadditive interaction between object and task switching, we additionally analysed the object repetition benefit when the task was switched. With two objects, switching tasks while repeating the object was 281 ms faster than switching both object and task, $t(19) = -8.16$, $p < .001$. This contrast increased to 368 ms with four objects, $t(19) = -8.57$, $p < .001$.

As expected on the assumption of parallel selection processes, object switching and task switching interacted underadditively. However, the difference between double switches and the condition in which only the object had to be switched while the task was repeated was relatively large, amounting to 169 ms (equally for two and four objects). Thus, this experiment shows some degree of interference between the switching processes but nevertheless is not compatible with the notion of a bottleneck that constrains both selection processes for both objects and tasks to run strictly serially. Substantial repetition benefits for objects while the task is switched rule out the hypothesis that objects and tasks are selected as integrated event files. Moreover, there was still a substantial effect of object set size on object-switch costs but not on task-switch costs. This effect supports the notion that objects compete for selection into the focus of attention, regardless of whether they are linked to their retrieval cues by long-term associations or by temporary bindings.

EXPERIMENT 4

So far, we have found evidence that selection of objects and tasks can proceed at least partially independently when one of them is retrieved via temporary bindings in WM and the other via more permanent associations in LTM (Experiments 1 and 3), but not when both must be retrieved via temporary bindings (Experiment 2). This raises the possibility that a retrieval bottleneck arises if and only if both selection processes must use the same kind of cue–target link: either temporary bindings or long-term associations. The last experiment tests this idea. In contrast to Experiment 2, in which objects and tasks were both linked to their retrieval cues by varied mappings, objects and tasks were now both assigned to a fixed mapping condition. The set of objects did not change throughout the whole experiment, like in Experiment 3. As in Experiment 1, addition was constantly associated to a red frame, and subtraction to a yellow frame. If object selection and task selection interfered with each other whenever the new object and the new task must be retrieved through the same kind of memory link—either associations in LTM or temporary bindings in WM—then the two selection processes should interfere in this experiment as in Experiment 2, and we should obtain additive switch costs. In contrast, if the two selection processes interfere only when they both must rely on bindings in WM, then they could run in parallel in the present experiment and generate underadditive switch costs.

Results and discussion

After removing errors and data trimming, 95% of the data was left for analysis. Results are illustrated in Figure 6. Both object and task switching main effects were significant, $F(1, 19) = 41.8$, $MSE = 75{,}388$, $p < .001$, and $F(1, 19) = 25.7$, $MSE = 25{,}467$, $p < .001$, respectively. Importantly,

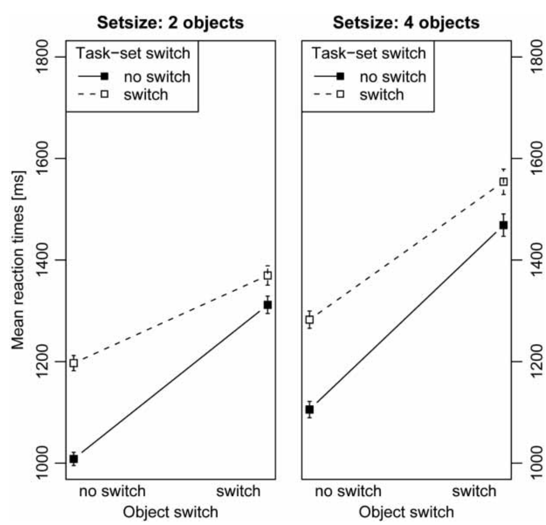

Figure 6. *Results of Experiment 4. The left panel shows reaction times with two objects; the right panel shows reaction times with four objects. Error bars are 95% confidence intervals.*

there was a significant underadditive interaction between object and task switching, supporting the assumption of parallel switching processes, $F(1, 19) = 46.2$, $MSE = 2{,}726$, $p < .001$. This interaction was not affected by the number of objects ($F < 1$). The number of objects had a significant main effect, $F(1, 19) = 18.7$, $MSE = 37{,}175$, $p < .001$, and it interacted again with object switching, $F(1, 19) = 9.0$, $MSE = 7{,}594$, $p = .007$, but not with task switching ($F < 1$). Object-switch costs increased from 239 ms with two objects to 322 ms with four objects. Task-switch costs only showed a slight increase from 125 ms to 131 ms with increasing number of objects.

To qualify the underadditive interaction, we again tested for object repetition benefits in the presence of a task switch. They amounted to 174 ms with two objects, $t(19) = -5.63$, $p < .001$, and 275 ms with four objects, $t(19) = -4.83$, $p < .001$.

Retrieving both objects and tasks via long-term associations resulted in an underadditive interaction between the switching processes. Although switching both object and task took somewhat longer than switching the object while repeating the task (59 ms with two objects and 84 ms with four objects), part of the switching processes nevertheless had to be accomplished in parallel. This result contrasts with evidence from other studies suggesting that retrieval from LTM is constrained by a bottleneck that permits retrieving only one representation at a time (Maylor et al., 2001; Rickard & Bajic, 2004). We return to the issue of serial versus parallel selection in the General Discussion.

The number of objects again only affected object switching and not task switching. Since this finding was reliable in all four experiments, it is strong evidence for the independence of maintenance of representations and selection processes, contrary to the hypothesis that they share a general executive resource.

GENERAL DISCUSSION

In four experiments we investigated the interaction pattern between object switching and task switching in a paradigm in which both objects and tasks were represented in memory. The pattern of interaction between object switching and task switching was used to investigate whether objects and tasks are represented and selected in a unitary way, or whether they are represented separately and selected in two processes, which can run either sequentially or in parallel. Across the four experiments we orthogonally manipulated the nature of the mapping of task cues to tasks and the mapping of object cues to memory objects; both mappings could be either fixed, as is typical in experiments on action selection and task switching, or varied, as is typical in experiments on WM and on switching between objects in WM. An additional manipulation of memory load enabled us to investigate the relationship between WM capacity and the executive processes of mentally switching objects and tasks.

The interaction between object switching and task switching differed between experiments (see Figure 7). When both mappings were varied, such that objects and tasks had to be retrieved through temporary bindings in WM, the two

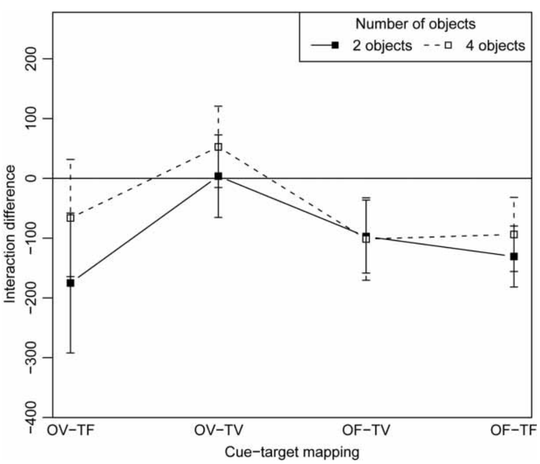

Figure 7. *The interaction of object switching and task switching as a function of mapping. Each data point reflects the interaction term from one experiment and one level of set size (two or four objects). The interaction term was computed as* $(RT_{object\ switch,\ task\ switch} + RT_{object\ repetition,\ task\ repetition}) - (RT_{object\ repetition,\ task\ switch} + RT_{object\ switch,\ task\ repetition})$. *Error bars are 95% confidence intervals. RT = reaction time. OV = object varied mapping. OF = object fixed mapping. TV = task varied mapping. TF = task fixed mapping.*

switching variables were additive. In all other cases we found evidence for an underadditive interaction. In addition, there was an effect of object set size (i.e., memory load) on object-switching costs but not on task-switching costs. This observation was independent of how objects and tasks were mapped onto their retrieval cues. We now discuss three implications of these results for our understanding of selection of representations in WM.

Selection mechanisms of objects and tasks

A first insight is that objects and tasks are selected separately, such that an object repetition benefit remains when the task is changed, and repeating a task shows a benefit when the object is changed. This conclusion follows from the finding of task-switch costs (or task-repetition benefits) in trials on which the object was switched and of object-switch costs (or object-repetition benefits) in trials on which the task was switched. If objects and tasks had been integrated into a unified whole that was selected as one, then any change of either the object or the task would have brought with it a change of the other part, such that changing both object and task would not cost more time than changing just one of them. This was not what we found.

One implication of having separate representations of objects and tasks is that there must be separate mechanisms for maintaining an object representation and a task representation in the state of being selected for (cognitive) action. The concept of a focus of attention in WM serves this function for objects; an analogous mechanism for tasks must be assumed to exist as an additional component of the WM system. This mechanism has been tentatively referred to as "procedural working memory" (Monsell, 2003; Oberauer, in press).

When objects and tasks are represented separately, they must be selected by two separate processes, and the question arises whether these processes are independent, so that they can proceed in parallel without mutual interference, or whether they compete with each other for a common mechanism or resource. A common mechanism that acts as a bottleneck for selection processes predicts additive time costs for object switches and task switches. A model of shared processing resource along the lines of Navon and Miller (2002) and Tombu and Jolicoeur (2003) makes the same prediction. In three out of four experiments, we found an underadditive interaction between object and task switching, as predicted by independent and parallel selection of both the relevant object and the relevant task. Even if both the relevant object and the relevant task could be retrieved through long-term associations (i.e., Experiment 4 with fixed cue–object and fixed cue–task mapping) there was evidence for at least partial independence of both selection processes. If it is assumed that using fixed mapping assignments results in the representations being held in LTM rather than in WM, underadditivity of the switching variables contradicts findings suggesting a selection bottleneck in LTM (Maylor et al., 2001; Rickard & Bajic, 2004). Our results are compatible, however, with other findings showing that at least under some circumstances information can be retrieved from LTM in parallel (Logan & Delheimer, 2001; Logan & Schulkind, 2000).

In contrast, if both representations had to be retrieved through temporary bindings in WM (i.e., Experiment 2 with varied cue–object and varied cue–task mapping), object and task switches were additive. Additive effects of object and task switching can be explained with a selection bottleneck in WM that forces the two selection processes to be executed in serial order or with separate mechanisms running in parallel but drawing on the same limited resource that slows down each selection process. The latter assumption gains plausibility due to the fact that additivity was found only if both object and task representations had to be selected through temporary bindings in WM, the only condition in which both selection processes should depend on executive attention conceptualized as a general and limited resource in WM (Kane & Engle, 2002; Lavie et al., 2004). However, this view also predicts that increasing the WM load by manipulating the object set size should affect both object- and task-switching processes.

The object set-size effect and executive control

One striking finding in the present experiments was that increasing the number of objects from which the relevant object had to be selected exerted a selective effect only on object switching and not on task switching irrespective of how objects and tasks were mapped onto their retrieval cues. Thus, even if both objects and tasks had to be selected through temporary bindings in WM, the object set size did not affect task switching. In the task-switching literature, the selection of the relevant task in the presence of irrelevant competitors is regarded as an instance of executive control (Logan, 2004; Mayr & Kliegl, 2000, 2003; Meiran, 1996; Rogers & Monsell, 1995). Assuming that WM capacity reflects a general resource of executive attention that has to be shared between object and task selection, increasing WM load from two to four objects should draw on the limitations of WM capacity and thus interfere with both switching processes. This is not what we found.

Taken together, our findings—in particular those from Experiment 2 with all varied mappings—create problems for an account in terms of shared resources, regardless of how they are carved up into separate resource pools. As argued above, the idea of a general resource of executive attention and WM does not account well for the data. One other possibility is to distinguish between resources for maintenance in WM and resources for executive processes such as selecting representations. That view would predict that the two switching costs are additive, as observed in Experiment 2, but it would also predict that neither switch cost is affected by memory load, contrary to our findings. Another way to distinguish resource pools is to distinguish resources for objects and resources for task sets, but that account cannot explain why selecting a new object and selecting a new task set compete with each other, as shown by additive time costs.

Therefore, we propose to abandon the idea of resources to explain why an increase in object set size increased RTs and object-switch costs. Instead, the object set-size effect is better explained as resulting from competition between selection candidates held in the direct access region of WM (cf. Oberauer & Göthe, 2006). On this account, objects do not compete for being selected as tasks, and their number will not interfere with task switching. In other words, the colours that act as cues for task sets do not cue representations of objects, so object representations do not get in the way of selecting the correct task set. At the same time, selection processes can be assumed to compete for a common mechanism or a common processing resource that is independent of how much the maintenance function of WM is loaded.

The object set-size effect and retrieval from LTM

The object set-size effect was observed even in the experiments that realized a fixed mapping between objects (i.e., digits) and their retrieval cues. This is noteworthy because the set of digits for which associations to spatial positions are learned over the course of the experiment is always four. Even when the given trial involves only two digits, LTM would contain all four cue–digit associations. The object set-size effect implies that, even though all four associations exist in LTM, only those needed in the current trial are relevant for RTs and object-switch costs. We take this as evidence that, even in the experiments with fixed cue–object mapping, objects are not retrieved from LTM directly. Rather, the relevant set of objects—either two or four, depending on condition—is "loaded" into the direct-access region of WM.[1] This means that

[1] In the condition with set size two, we always used the same two digits. Thus, one could argue that although all four digit–cue associations are well learned, the subset of two digits that are used in the set size two conditions are learned better and, thus, can be retrieved faster. To address this possibility, we ran the analysis of set-size effects in Experiments 3 and 4 again, using only those RTs that required access to one of the two digits that were used in both the small and the large set-size conditions. For this comparison, cue–digit associations in LTM must be equally strong in the set size two and set size four conditions. The interaction between object switching and object set size was still significant in Experiment 3, $F(1, 19) = 11.5$, $MSE = 10{,}691$, $p = .003$, and in Experiment 4, $F(1, 19) = 23.0$, $MSE = 3{,}193$, $p < .001$. Therefore, the set-size effect cannot be due to differential practice of the cue–digit associations.

temporary bindings are established between the frame locations and the digits, matching the associations in LTM. Thus, the present findings support one assumption of the theoretical framework of Oberauer (2002, 2006, in press): Representations that are required as input for cognitive processes must be held in the region of direct access, even when they are at the same time well represented in LTM. Furthermore, only the objects held in the region of direct access compete for selection—that is, for being accessed by the focus of attention—whereas objects in the activated part of LTM have no influence on RTs and object-switch costs.

Priming and selecting representations

The different pattern of interaction between object switching and task switching across the mapping conditions of our four experiments can be explained by drawing on the distinction between selection of representations (i.e., of objects and of task sets) and priming of those representations. In a review of the dual-task literature, Lien and Proctor (2002) have argued that what evidence exists for processes bypassing a hypothetical response selection bottleneck is best explained as priming, but not selecting, a response. The difference between priming and selecting is that priming only preactivates a representation without making a commitment to selecting it to the exclusion of alternatives. A primed response would be easier to select than an unprimed one, but as long as it is not selected in addition to being primed, it is not executed. Applied to our experiments and following the above argumentation, we could assume that both object and task selection processes require a capacity-limited mechanism that acts as a bottleneck (i.e., permitting only one selection process at a time). These selection processes draw on temporary bindings between the targets of selection (i.e., the objects and the task sets) and the cues that indicate which object and which task to choose. When both cue–object mappings and cue–task mappings vary from trial to trial, only those temporary bindings are available, and the selection processes are additive in time. When one or both of these mappings are constant across trials, long-term memory associations between cues and objects, or between cues and tasks, or both, are built up. They mediate activation from the perceived cues to the representations associated to them, thus priming the corresponding tasks and objects. Transmitting activation through long-term memory associations is assumed to occur in parallel with selection processes and not compete with selection for any mechanisms or resources. In trials in which both a new object and a new task must be selected, the selection processes would still proceed one after the other. However, concurrent with the first selection (e.g., the new task), the target of the second selection (e.g., the new object) is already primed. Priming the new object during selection of the task preactivates it significantly above baseline and thus speeds up its following selection. As a consequence, the total time for switching both object and task is faster than the sum of the times for selecting each of them alone. Priming results in a measurable benefit only in the case of two switches because only the representation selected second benefits from the accumulation of activation during the selection of the representation selected first (for an illustration see Figure 8). No underadditive interaction between object switching and task switching is expected when both objects and tasks are linked to their cues by temporary bindings rather than associations in LTM, because activation spreads only along associations in LTM.

This view implies that associations in LTM are not sufficient to mediate selection; they only provide priming. Thus, even when associations between cues and memory objects, or between cues and tasks, have been built in LTM, actual selection of a new object or a new task can occur only when temporary bindings, which mirror the long-term associations, are established between the objects and their cues, or between the tasks and their cues. This hypothesis matches well with the finding that even when the cue–object mappings are constant across all trials and therefore can be encoded into LTM, set-size effects for the set that is relevant in each trial are observed, indicating that the relevant set is selectively

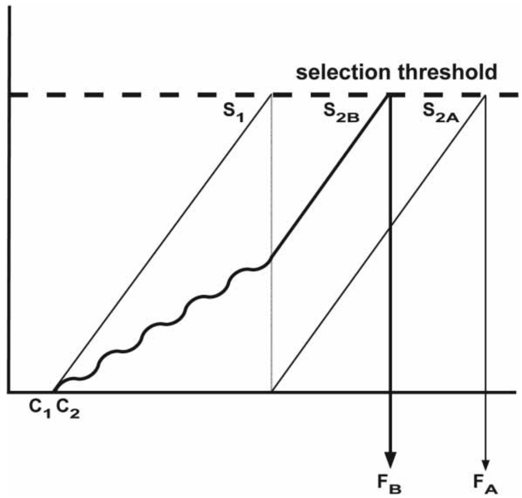

Figure 8. *Illustration of how priming around the bottleneck reduces reaction times if both object and task have to be switched. Immediately after presentation of the cues (C_1 and C_2), information begins to accumulate for the first selection process (S_1), which is completed once a threshold is reached. If the cue–target mapping is varied, selection of the second element cannot start before S_1 has terminated (S_{2A}). If the cue–target mapping is fixed, selection can be primed during S_1, reducing the time for the second selection process (S_{2B}). Thus, finishing times are shorter in the case of priming (F_B) than when priming is absent (F_A).*

"loaded" into the direct-access region. The function of the direct-access region is to hold temporary bindings between memory objects and their context (such as their spatial location), and these bindings are needed for selecting one object into the focus of attention.

Such a system might sound overly complicated—why double associations in LTM by building parallel bindings in the direct-access region? The duality of associations and bindings, however, serves a purpose: Whereas spreading activation along associations in LTM can prepare many potentially relevant representations simultaneously—among them incompatible representations, such as the results of arithmetic operations applied to different numbers—these associations do not control our thought and action. Control is the privilege of those representations that are held in the region of direct access and of the relations between them that are established by temporary bindings. In this way, the system can flexibly set up control structures, such as ordered sets of objects, as well as task sets, and these structures can mirror learned associations in LTM but can also go against them. In the latter case, the ad hoc structures must be able to dominate those held in LTM—for instance, even though we have firmly established the sequence "1, 2, 3, 4, 5" in LTM, we can recall a new random sequence of digits given to us for the current trial in an experiment such as the ones we conducted. Thus, even strong associations in LTM usually do not take over control because their influence is limited to priming representations, whereas actual selection is guided by the temporary bindings that create structures in the region of direct access. Whenever the task requires access to a set of objects, such that on each step of the task one object in the set must be selected, then the whole set must be held in the direct-access region of WM. This is the case regardless of whether the set is a new one, as in our experiments with varied cue–object mappings, or a well-learned one, as in our experiments with fixed cue–object mappings. In contrast, information that is not currently needed for processing, such as the "passive" lists in the experiments in Oberauer (2002, 2005), can be outsourced into the activated part of LTM and thus generates no set-size effect on latencies.

CONCLUSION

To conclude, the results reported here add important aspects to a differentiated view of WM. The findings suggest that object switching and task switching reflect two distinct subsystems that can be conceptualized as the declarative and procedural part of WM. Increasing the load on the declarative part of WM did not affect the procedural part, contrary to the view of a general resource of executive attention responsible for both short-term maintenance and control processes. Selection of objects and tasks, however, seems to be restricted by a common selection bottleneck. We propose that the bottleneck can be bypassed by priming when one of the selection targets can be preactivated through well-established cue–target associations. Selected objects and selected tasks are represented separately, implying that a mechanism such as the focus of attention for objects must also exist for maintaining the currently selected task.

Original manuscript received 19 January 2009
Accepted revision received 27 May 2009
First published online 9 September 2009

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