

**Focus switching in working memory: the roles of context access and content
retrieval**

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Abstract

Focus switching in working memory involves accessing an object in the focus of attention in order to retrieve its content. Objects in working memory can be viewed as consisting of two types of information: contents (e.g., numerical information) and contexts (e.g., cues to retrieve the contents). This study examined the extent to which content retrieval and context access may be separated. Three experiments were carried out in which object switching and content retrieval were manipulated. In addition, the alternation between the retrieval operations was also manipulated. The main result was that content retrieval required time over and above that needed to access the object. This finding supports the idea that contexts and their contents may be accessed independently when an object is brought into the focus.

Keywords: focus switching, object switching, retrieval, task switching, working memory, working memory updating

Focus switching in working memory: the roles of context access and content retrieval

Focus switching is a process that enables information maintained in working memory (WM) to be activated in the focus of attention. The focus of attention is the region of WM in which the information is immediately accessible for cognitive operations. Only a very restricted subset of elements maintained in WM may be in the focus of attention at any given time. Indeed, many authors argue that only one item representation can be held in the focus (Garavan, 1998; McElree, 2006; Oberauer, 2002; but see also Gilchrist & Cowan, 2011; Oberauer, 2013). This severely limited capacity calls upon a mechanism that quickly and accurately switches information in and out of the focus. This focus switching mechanism has been considered an executive control process independent from other processes such as updating and task switching (Verhaeghen & Hoyer, 2007). The present study aimed to better understand how information is retrieved in the focus of attention.

Activating an object in the focus, or switching from one element to another, takes time. Garavan (1998) demonstrated this time cost using a dual-counter task that required participants to keep a running count of a sequence of triangles and rectangles that were presented randomly. When different figures were presented consecutively (e.g., rectangle followed by triangle), response times for increasing the counter were around 500 ms slower than when the same figure was repeated in two successive trials (e.g., triangle followed by triangle). The author interpreted this object-switching effect as a consequence of the attentional shifting from one element in WM to another. Subsequently, this switching cost has been evidenced in numerous studies and with different paradigms (Janczyk & Grabowski, 2011; Kessler & Meiran, 2006; Kübler,

Murphy, Kaufman, Stein, & Garavan, 2003; Oberauer, 2001, 2003; Verhaeghen, Cerella, & Basak, 2004).

Following on from Garavan's early work, some research has been undertaken to isolate different components at play in the object-switching effect. Oberauer (2003) investigated whether updating and selective access to objects contributed separately to the focus-switching effect. Across two experiments, participants were asked to apply arithmetic operations (e.g., +1) to digits associated with different objects in WM without updating their values. Given that the information had to be accessed but not updated, the extra time required when accessing a different element was interpreted as the cost for switching the focus of attention between objects in WM. In a further experiment, the task involved solving simple operations (e.g., 5 - 2) whose results came to replace previous values associated with the corresponding element in WM. A switching effect was also observed in this task which required updating but not access to any information in WM. The time cost in this case had to be attributed to other processes that included: bringing the representation about the position of the object into the focus of attention or binding the element active in the focus to its context (e.g., spatial location, serial order position) in WM.

A relevant issue in explaining the focus-switching mechanism is how objects in WM are accessed. Objects in WM may be considered composites of two different types of information: contexts and contents (e.g., Bialkova & Oberauer, 2010). Contexts refer to any cues – spatial locations, colours, serial positions, etc. – that may serve to address the contents. Meanwhile, contents are information associated with an object (e.g., numerical representations) to which cognitive operations can be applied. Some studies have examined how access to the context and retrieval of the content might influence focus switching.

Access to the context is essential in these types of tasks. Usually a stimulus or specific features of the stimuli (e.g., shape, colour, location, serial position) are used as cues to identify the appropriate object in WM. Gehring, Bryck, Jonides, Albin, and Badre (2003) observed that two different cues can be used to access the same object. This means that the same content may be addressed by different contexts.

The nature or type of context may affect focus switching. Verhaeghen et al. (2004; see also Verhaeghen & Basak, 2005) studied object switching by using the n-back task, comparing 1-back (no switching) and 2-back (switching) performance. They developed a modified n-back task in which information was presented in columns, thus making it easier to identify the position of each item. The switching cost was found to be lower in the modified task than in the standard n-back task (Vaughan, Basak, Hartman, & Verhaeghen, 2008). This suggests that some information conveyed by the cue may facilitate content access.

The content has also proved to contribute to the focus-switching effect. Schwager and Hagendorf (2009) showed that focus switching is determined by the task goal and ultimately by the information required to perform the task. Thus, the switching cost may change depending on the informative demand of the task. In their study, one condition called upon participants to retrieve a number and use its semantic features (e.g., numerical magnitude), whereas another condition made it possible to use only phonological information. Results showed that when the task required the retrieval of more complex information related to the object (e.g., semantic), the object-switching cost was larger than when the task could be executed with comparatively more superficial information (e.g., phonological), even when both conditions involved the same numbers. Therefore, content access seems to influence the focus-switching process.

Decomposing focus switching

Previous studies have shown how factors related to both context access and content retrieval influence the speed with which an object is activated in the focus of attention. However, it is unclear whether both processes operate simultaneously or sequentially. In this regard, Bialkova and Oberauer (2010) put forward two alternatives. First, context and content are bound, which means that context access simultaneously entails content retrieval. In this case, content retrieval would not incur an additional time cost. Second, context is accessed first and then serves as a cue to retrieve the content. Thus, accessing a representation would involve two steps: context access followed by content retrieval. If this occurs, both processes would, to some extent, contribute separately to determining the focus-switching cost.

To investigate this matter further, Bialkova and Oberauer (2010) used an arithmetic task in which three initial numbers were presented successively in three different colours that participants should hold in WM. Each colour served as a cue to identify one object in WM. Once the numbers associated with each colour were memorized, different arithmetic operations were then displayed in one of the three colours. Participants had to perform the operation and memorize the result associated with each colour in anticipation of having to use it in the next operation. To manipulate content retrieval, two types of operations were included: complete (e.g., $4 + 1$), which did not involve content retrieval because both operands were presented, and incomplete (e.g., $+ 1$), which required content retrieval because participants had to retrieve the first operand from WM (i.e., the number previously memorized for that colour). Regarding context access manipulation, there were two conditions: object switching, where two consecutive items were of different colours, and non-object switching, where the same colour was used for two consecutive items. In their second experiment, a clear object-

switching cost was found for response times; however, a content-retrieval cost was not evident. Therefore, content retrieval did not appear to imply an additional cost to be added to context access. A conclusion drawn is that context and content are bound together, meaning that they are simultaneously activated in the focus of attention.

Despite the evidence, there has been little examination into how object context and object content are accessed in the focus of attention. Linares, Bajo, and Pelegrina (2016) administered an arithmetic updating task to different groups of children and adolescents, which could also provide additional information. In the task, participants had to apply different arithmetic operations to initial numbers that appeared in two possible boxes and memorize the result for each box because it could be used afterwards. In some lists, all items comprised incomplete arithmetic operations (e.g., $? + 1$), which meant retrieving the number associated with the box. In other lists, all items involved complete arithmetic operations (e.g., $3 + 1$), which did not require content retrieval. Each list also featured object repetition and object switching, that is, the two different conditions related to context retrieval. Although the task was designed to only manipulate content retrieval, a reanalysis of non-published data covering context access and content retrieval revealed that both factors had a separate effect on response times. From these interim results, it would appear that both factors contribute separately to the focus-switching process. It would be necessary, however, to take this further in a study specifically designed to address this particular issue.

The present study

The goal of the present study was to reinvestigate whether object switching can be decomposed into two processes. In these experiments, we used an adapted version of the numerical updating task devised by Bialkova and Oberauer (2010). Initially, participants were asked to memorize two digits associated with two figures. They then

had to apply different arithmetic operations that would appear inside of one of the figures and use the result to update the digit of the corresponding figure. There were incomplete operations (e.g., $\cdot + 1$), which required access to the content (indicated here by the middle dot), and complete operations (e.g., $3 + 1$), which enabled participants to perform the operation without having to access the content. In addition, there were object repetitions and switches depending on whether the figure was the same as or different to the previous one. When different figures were presented in two consecutive trials (i.e., object switching), context access was required.

In this task, as with those used by Oberauer (2003) and Bialkova and Oberauer (2010), frequent switches took place between the two types of retrieval operations instantiated by complete and incomplete operations. This could induce a task-switching effect; in other words, repeating the same retrieval operation (e.g., a complete operation “ $3 + 1$ ” after another complete operation “ $4 - 1$ ”) would take less time than using a different type of retrieval operation in two consecutive items (e.g., a complete operation “ $3 + 1$ ” after an incomplete operation “ $\cdot - 1$ ”). Taking into account the alternation between retrieval operations may prove important given that previous research has shown how task switching interacts with object switching. Specifically, the object-switching cost is smaller in task-switching trials than in task-repetition trials, at least when the mapping between cues and objects or tasks remains the same across trials (Risse & Oberauer, 2010; Verhaeghen & Basak, 2005; but see Verhaeghen & Hoyer, 2007). This suggests that the two switching processes or some of their components can be partially executed in parallel.

Given the previously observed interaction pattern between object switching and task switching, we administered simple lists featuring both types of retrieval operations separately, thus following the procedure by Linares et al. (2016). In addition, and in line

with earlier experiments by Bialkova and Oberauer (2010), we included mixed lists that covered both types of retrieval operations. Thus, content retrieval and object-switching costs could be analyzed in both presence and absence of retrieval operation switches. We expected to find an object-switching effect that would produce underadditive interactions with retrieval-operation alternation in line with previous studies (Risse & Oberauer, 2010; Verhaeghen & Basak, 2005). Specifically, the object-switching cost should be higher when the retrieval operation is repeated than when the retrieval operation is different to the previous one.

Regarding the issue most relevant to the present study, namely the effect of content retrieval, two possibilities were considered (see Bialkova & Oberauer, 2010). The first alternative posits that context and content are accessed simultaneously. Once the context is accessed (i.e., when the object switches), the retrieval effect would be absent; in other words, incomplete and complete operations would take the same time. The second possibility is that content retrieval occurs after context access. In this case, a certain amount of time to retrieve the content should be added to the time required to access the context, but only when the object switches. In contrast, when the object is repeated, there would be no need to retrieve the content because it is already in the focus of attention. Content retrieval should then be immediate.

Experiment 1

In the first experiment, object switching, content retrieval and retrieval operation alternation were manipulated simultaneously. Object switching refers to whether an object is repeated or differs from that of the previous item. Thus, two conditions were set up: object repetition, where the object was repeated in two consecutive items and therefore the context remains the same, and object switching, where different objects

were presented in two consecutive items and thus the context changes. Content retrieval indicates whether the information associated with an object has to be retrieved from WM. Two conditions were addressed: non-retrieval, where all the information was presented, that is, two operands and the arithmetic symbol of the operation (e.g., $4 + 1$), and retrieval, namely when the first operand in the equation had to be retrieved to perform the arithmetic operation (e.g., $\cdot + 1$). Lastly, retrieval operation alternation looks at whether the retrieval operation condition is repeated or not in consecutive trials. A between-list design was used which included single lists (featuring only one type of retrieval operation) and mixed lists (with both types of retrieval operations). Thus, in single lists, the same retrieval operation was presented consecutively, that is, complete operations that do not involve retrieval (e.g., " $4 + 1$ " followed by " $5 - 2$ ") or incomplete operations that did require retrieval (e.g., " $\cdot + 1$ " followed by " $\cdot - 2$ "). In mixed lists, both retrieval operations were included. This meant that retrieval operation switches could occur in consecutive trials (e.g., " $4 + 1$ " and then " $\cdot - 2$ "), as well as retrieval operation repetitions. This design enabled us to compare performance across the two types of lists used in previous studies: mixed lists as in Bialkova and Oberauer (2010) and single lists as in Linares et al. (2016).

Method

Participants

Twenty-four students from the University of Jaén (Spain) aged 19 to 24 years ($M = 20.63$, $SD = 2$) (5 males and 19 females) participated in this experiment. Sample size was selected to be similar to previous studies by Bialkova and Oberauer (2010). All participants took part voluntarily and gave their written informed consent prior to starting the experimental session. They received course credits for participating.

Material

The experiment comprised 80 lists of 6 to 12 items. Lists varied in length to prevent participants from predicting the end of each list. The first two items were a digit (ranging from 3 to 9), which was presented inside one of two possible shapes: a red square or a blue triangle. The first item in the list was always the red square followed by the blue triangle. The remaining items were complete or incomplete arithmetic operations that appeared inside one of the shapes. The first operand could be a digit from 3 to 9 or a middle dot (\cdot). The operation and the second operand could be +1, -1, +2 or -2. Thus, there were items with incomplete operations that included only the second operand (e.g., $\cdot + 1$) and items with complete operations that displayed both operands (e.g., $4 + 1$). It should be noted that, to minimize interference between the two operands, the sets of possible digits for each one were different (3 to 9 for the first operand and 1 or 2 for the second). For both types of operations (complete and incomplete), the to-be-memorized digits were determined on the basis of the digit maintained in memory rather than being selected at random as in Bialkova and Oberauer's (2010) study. Thus, if the content associated with an object was the number 4 and the operation to be applied was +1, the item "4+1" was generated as a complete equation, and the item " $\cdot + 1$ " as an incomplete equation. In each case, the new to-be-memorized digit would be the same: the number 5 in the example above. This ensured that the to-be-updated number and the new one were similar across both conditions, for example, in terms of numerical distance which could affect updating times (see Lendínez, Pelegrina, & Lechuga, 2011, 2014).

Items varied in type according to the object-switching and content-retrieval conditions. In the object-repetition condition, the object (e.g., red square) was the same as in the previous item, whereas the object differed from the previous item in the object-

switch condition. In the non-retrieval condition, complete operations were presented (e.g., $3+1$), whereas in the retrieval condition, incomplete operations appeared in which the first operand was indicated by a middle dot (e.g., $\cdot + 1$). Each item was randomly assigned to one of the levels corresponding to the previous conditions. There were approximately 70 items for each condition across all lists. These conditions were distributed similarly across all serial positions in the lists.

Retrieval operation alternation was manipulated through the type of list. Two sets of single and mixed lists were created (see Figure 1). The single lists included items from only a content-retrieval condition, so that they involved the repetition of the retrieval operations. Thus, there were 20 single lists with items from the retrieval condition that included only incomplete operations (e.g., $\cdot + 2$) and 20 single lists with items from the non-retrieval condition that included only complete operations (e.g., $5 + 2$). There were also 40 mixed lists that contained items from both content-retrieval conditions randomly assigned to the different serial positions. In these lists, alternation between retrieval and non-retrieval items was possible. In the experimental session, the lists were organized into three blocks following a block-sandwich design (see Kessler & Meiran, 2006). The first and third blocks each included 20 single lists. In the first block, half of the lists were made up of non-retrieval items and the remaining lists included only retrieval items. The second block comprised 40 mixed lists. The third block featured retrieval-only items in the first half of the lists and non-retrieval items in the second half. A main advantage of this design is that it enables us to control for the effects of practice. On average, the amount of training is the same in both single and mixed lists.

The lists were created using a computer programme that randomly selected the initial numbers for each figure and established the specific conditions for all remaining

items according to the previous specifications. The programme calculated and updated the numerical value of the items for each object, and this value was used for constructing the operations of each item when necessary (i.e., the first operand in the complete operations under the non-retrieval condition). A different set of lists was produced for each participant.

Procedure

Each list began with the consecutive presentation of the two initial items, one for each object (red square and blue triangle). Participants were asked to press the space bar when they had memorized the number associated with each object (e.g., 3 for the red square). After the initial items, the remaining items were presented consecutively. For each item, participants had to solve an arithmetic operation (e.g., $3+1$), memorize the result for the corresponding object, and press the space bar to proceed with the next item. When the item belonged to the retrieval condition (e.g., $\cdot + 1$), participants had to use the previously memorized number for said object as the first operand, indicated by the middle dot. A blank screen lasting 250 ms was shown between two consecutive items. At the end of the list, the two shapes were presented and participants had to type the last result associated with each one, first the red square followed by the blue triangle. Participants then received feedback on the number of correct answers.

(Please insert Figure 1 about here)

E-Prime 2.0 (Schneider, Eschman, & Zuccolotto, 2002) was used for presenting stimuli, registering times and recording responses. The dependent variables were the percentage of correctly recalled numbers and response times.

Prior to the experimental session, participants were given instructions and were asked to be as fast and accurate as possible. They completed nine practice trials covering all types of lists, so that they were familiar with the procedure. Task administration took place inside an individual cubicle, lasting approximately 45 minutes. A 15.6-inch colour monitor was used.

Results

One participant was removed from the analyses because of their low percentage of recall (67.83%). Participants correctly recalled 92.8% ($SD = 6.01$) of all lists. Response times made on incorrect and practice lists were excluded from analysis. All response times under 200 ms and those greater than the participants' mean times in each condition plus 3.5 standard deviations were also removed prior to analysis. This represented 1.16% of the observations. Figure 2 shows the mean response times for each condition.

A 2 x 2 x 2 analysis of variance (ANOVA) was performed on response times with list type (single list and mixed list), object switching (object-switching and object-repetition) and content retrieval (retrieval and non-retrieval) as within-participant factors. The test statistics are summarized in Table 1.

(Please insert Table 1 about here)

The main effects of list type, object switching and content retrieval were significant. The list type x object switching and object switching x content retrieval interactions reached significance, whereas the list type x content retrieval interaction

failed to do so. Previous results were qualified by the three-way interaction between list type, object switching and content retrieval.

We were interested in determining a possible simultaneous effect of both object switching and content retrieval on response times. Therefore, the three-way interaction was further specified by a separate two-way ANOVA 2 (object switching) x 2 (content retrieval) for each list type. The separate analysis for the single lists revealed the main effect of object switching to be significant, whereas content retrieval did not reach significance. The interaction also proved significant, indicating an opposite effect of content retrieval on each level of object switching. As expected, content retrieval incurred a cost of 200 ms when an object switch was required, $F(1, 22) = 35.18, p < .001, \eta_p^2 = .62$. However, and unexpectedly, content retrieval produced a benefit of 168 ms in the object-repetition condition, $F(1, 22) = 11.77, p = .002, \eta_p^2 = .35$. Thus, when the object was repeated in the single lists, participants spent less time having to retrieve the object's numerical content (incomplete operations) than when all information needed to perform the operation was presented.

The analogous analysis for mixed lists showed the significant effects of object switching and content retrieval as well their interaction. Once again, content retrieval produced a cost (163 ms) when an object switch occurred, $F(1, 22) = 13.99, p = .001, \eta_p^2 = .39$. However, when the object was repeated, no differences due to content retrieval were observed, $F(1, 22) = 0.40, p = .535, \eta_p^2 = .02$.

(Please insert Figure 2 about here)

Discussion

This experiment has shown that the three factors considered (object switching, content retrieval and retrieval operation alternation) produced the expected differences in response times.

The results suggest that context access and content retrieval might be separate processes. The retrieval of information associated with the object incurred an additional cost in some conditions. On the one hand, when there was an object switch and then context access was required, retrieving the content (incomplete operations) took additional time compared to the condition in which content retrieval was not necessary (complete operations). The retrieval cost was evidenced across both single and mixed lists. This result, which differs from that reported by Bialkova and Oberauer (2010), suggests that context access precedes, to some extent, content retrieval.

On the other hand, when the object was repeated, the pattern of results was more complex. In mixed lists, content retrieval did not produce an additional time cost. At a first glance, this finding seems logical, taking into account that all information in object-repetition trials would be active in the focus of attention and no retrieval would be required even when an incomplete operation was presented. It is of note, however, that the mixed lists comprised two types of trials: those in which the retrieval operation was repeated and those in which the operation was different to that of the previous item. In view of this, it would be worthwhile separately analyzing both trial types to determine whether or not the content retrieval effect is similar across both. This would be an aim in follow-up experiments.

Unexpectedly, when the same object was repeated in single lists, items with incomplete operations required less time than those with complete operations. Therefore, a time benefit rather than a time cost was associated with content retrieval.

There are two possible explanations for this result. The first has to do with the number of to-be-codified elements. When a complete operation is presented, both operands have to be codified and activated in the focus of attention in order to perform the operation. However, in the case of incomplete operations, only the second operand requires activation because the first one is already in the focus. It is important to note that this facilitation only occurs when the retrieval operation is repeated. In this condition, the operation is ready to be applied to the active element in the focus. However, when the retrieval operation switches, this time advantage disappears. This may be because the retrieval operation requires binding to the new object, and only then can the content be retrieved.

Another possibility is that in simple lists, when incomplete operations are presented, participants progress quickly through the lists because they rely on memory to perform the next operation. Once the arithmetic operation has been completed, a faster pace may provide fewer opportunities for memory content to degrade. It may have even been the case that participants, in the incomplete operations condition, used the time between stimuli (250 ms) to complete the operation and substitute the information. As for the simple lists with complete operations (non-retrieval), participants may have performed the operations and substituted the information at a somewhat slower pace, given that the operations remained on the screen. A feature of the task likely to have contributed to this strategic bias is that participants were not required to type the results for each operation.

Lastly, it is worth noting that the interaction between object switch and retrieval operation alternation was significant. Switching cost was higher (363 ms) when the retrieval operation was repeated than when it was different (250 ms). This underadditive interaction is compatible with the conclusion drawn by Risse and Oberauer (2010) that a

new task and a new object can be accessed in parallel. This would imply that both processes do not compete for the same mechanism, and is consistent with the framework proposed by Oberauer (2009) in which declarative and procedural WM are separate and, to a large extent, independent of each other (but see Janczyk, 2017, for a different view in which procedural and declarative WM rely on a shared resource).

Experiments 2a and 2b

In the previous experiment, retrieval operation alternation was studied using single and mixed lists. As the mixed lists comprised items in which retrieval operations were either switched or repeated, the results in these lists reflect the effects of both types of operations. It was considered opportune to analyze whether retrieval operation alternation within mixed lists induces differences in the retrieval cost similar to that found in the previous experiment. It was also deemed particularly necessary to replicate whether content retrieval produced a time benefit instead of a time cost when both object and retrieval operation were repeated.

Two experiments (2a and 2b) were run to replicate Experiment 1, using only mixed lists. The aim of these experiments was twofold: first, to confirm whether content retrieval requires additional time following context access (i.e., object switching); and second, to corroborate the retrieval benefit when both object and retrieval operation are repeated. Only mixed lists were used in these experiments, doubled in number compared to the first experiment. This would make it possible to separately analyze consecutive trials in which the retrieval operation is repeated and where trials are different. We expected to observe a retrieval cost when an object switch occurs and a retrieval benefit in object-repetition trials when the same retrieval operation is repeated.

In the previous experiment, participants had to press a key to view the next item. In the first version of the second experiment, we used the same self-paced procedure, whereas the second version required participants to enter the result for each operation. Thus, errors could also be analyzed.

Method

Participants

Twenty-four students from the University of Jaén (Spain) aged 18 to 48 years ($M = 22.83$, $SD = 8.34$) (2 males and 22 females) participated in Experiment 2a. One participant was replaced because he or she had taken part in the previous experiment. Experiment 2b involved 24 university students aged 18 to 23 years ($M = 19.46$, $SD = 1.93$) (8 males and 16 females). As in the previous experiment, all participants volunteered for the study and received course credits for their participation. Written informed consent was obtained prior to starting the experimental session.

Material and procedure

The same task described in the first study was administered in Experiments 2a and 2b, but this time only mixed lists were included. A total of 80 mixed lists were created for each subject. As in the previous experiment, items varied in type according to the object switching and content retrieval conditions. Furthermore, alternation between retrieval operations was also manipulated. Thus, the retrieval operation for half of all items was the same as for the previous item, whereas the retrieval operation for the other half was different to that of the preceding item. There were approximately 60 items for each condition across all lists. The only difference in Experiment 2b was that participants had to enter the result after performing each operation. This would allow for data collection on accuracy.

The same procedure was used as in the previous experiment and task administration also lasted 45 minutes.

Results

Experiments 2a and 2b used the same analysis as employed in the previous experiment, although this time retrieval operation alternation acted as the independent variable in place of list type. As in the previous experiment, all response times under 200 ms and those greater than the participants' mean times in each condition plus 3.5 standard deviations were also removed prior to analysis. This represented 1.18% of observations in Experiment 2a and 1.03% in Experiment 2b. In addition, response times to items at serial position 3 in both experiments were excluded. The retrieval operation alternation level for this item could not be determined since items at positions 1 and 2 did not involve operations. Finally, given that accuracy was measured in Experiment 2b, reaction times associated with incorrect responses in this experiment were excluded from analysis. This represented 2.66% of all observations. Figures 3 and 4 show the mean response times for each condition in Experiments 2a and 2b, respectively.

Thus, A 2 x 2 x 2 analysis of variance (ANOVA) was performed on response times as well as on accuracy in Experiment 2b, with retrieval operation alternation (retrieval operation repetition and retrieval operation switch), object switching (object-switch and object-repetition) and content retrieval (retrieval and non-retrieval) as within-participant factors.

Experiment 2a. Two participants were excluded from the analyses. One appeared to misunderstand the instructions (12% of recall) and the other showed low recall performance (65%). Participants correctly recalled 91% ($SD = 7.02$) of all lists.

As in the previous experiment, the three-way interaction between retrieval operation alternation, object switching and content retrieval reached significance (see

Table 1). To analyze the three-way interaction, a two-way ANOVA 2 (object switching) x 2 (content retrieval) was performed on each retrieval operation alternation condition. The separate analysis for the retrieval operation repetition condition revealed a significant interaction between object switching and content retrieval that was due to an opposite effect of content retrieval on each level of object switching. As with the first experiment, content retrieval in the object-switch condition incurred a cost of 165 ms, $F(1, 21) = 8.04, p = .01, \eta_p^2 = .28$. In contrast, when an object repetition occurred, content retrieval produced a benefit of 198 ms, $F(1, 21) = 16.86, p = .001, \eta_p^2 = .45$. Thus, when both retrieval operation and object were repeated, participants spent less time on incomplete than on complete operations.

The analogous analysis for the retrieval operation switch condition showed only significant main effects of object switching and content retrieval.

Experiment 2b. In this experiment, the same analysis as previously performed in Experiment 2a was carried out on response times and accuracy. Participants correctly recalled 93.6% ($SD = 5.44$) of all lists.

Response times. Table 1 summarizes the ANOVA test statistics. As in the previous experiments, the three-way interaction between object switching, content retrieval and retrieval operation alternation was significant. The three-way interaction was further specified by a separate two-way ANOVA 2 (object switching) x 2 (content retrieval) for each retrieval operation alternation condition. The separate analysis for the retrieval operation repetition condition revealed that the interaction between object switching and content retrieval proved significant, indicating a different effect of content retrieval on each level of object switching. As in previous experiments, when the object was repeated, content retrieval produced a benefit of 264 ms, $F(1, 23) =$

39.44, $p < .001$, $\eta_p^2 = .64$. However, in this experiment, content retrieval did not incur a noticeable cost when an object switch occurred, $F(1, 23) = 0.95$, $p = .341$, $\eta_p^2 = .04$.

The analogous analysis for the retrieval operation switch condition showed the significant effects of context access and content retrieval. Their interaction did not reach significance.

Accuracy. The three-way interaction between object switching, content retrieval and retrieval operation alternation reached significance (see Table 1). A two-way ANOVA 2 (object switching) x 2 (content retrieval) was performed in order to analyze the three-way interaction for each retrieval operation alternation condition. The separate analysis for the retrieval operation repetition condition revealed only a significant effect of content retrieval. Neither object switching nor interaction proved significant.

The analogous analysis for the retrieval operation switch condition indicated that both main effects (object switching and content retrieval) reached statistical significance, but not their interaction.

(Please insert Figure 4 about here)

Discussion

As with the first experiment, the results suggest that focus switching may entail at least two subprocesses: context access and content retrieval. In addition, content retrieval produced a different effect depending on the retrieval operation alternation and object switching. Results for each retrieval alternation condition are discussed below.

When the retrieval operation was different from that of the previous trial, a retrieval effect was observed. Thus, more time was spent on incomplete operations than on complete operations that did not require content retrieval. As in the first experiment, this effect was observed in the object-switch condition, but also in the object repetition condition. This last finding appears to be at odds with observations made in the

previous experiment, where no retrieval cost was observed when the object was repeated and the retrieval operation switched. In said experiment, this condition was studied using mixed lists. Thus, the absence of retrieval cost could be the result of the opposite effects of each type of item included in these lists: cases where the retrieval operation was repeated and where the retrieval operation differed from the previous item.

The pattern found for errors made following retrieval operation switches coincided with that of response times. It should be noted that this effect is similar to that described for errors by Bialkova and Oberauer (2010). Therefore, the present experiments, which were designed to better analyze the effect of retrieval operation alternation, revealed a content-retrieval cost provided that retrieval operation alternation takes place.

When the retrieval operation was repeated, the pattern observed was generally consistent with that seen in the previous experiment using single lists. First, when the object was repeated, content retrieval produced a benefit. Specifically, incomplete operations, which require content retrieval, took less time compared to complete operations, where retrieval is not necessary.

It should be noted that the time benefit resulting from object and retrieval operation repetition was not accompanied by a similar effect on error rates. Here, however, a content-retrieval cost was observed. The divergence in the effects on errors and response times corresponding to this condition is compatible with a dissociation between availability (errors) and accessibility (response times) of information in WM (see McElree, 2001; Vaughan et al., 2008; Verhaeghen & Basak, 2005). It would seem to indicate that item availability and accessibility rely on different mechanisms. On the other hand, the different patterns obtained for both dependent variables in this condition

may be indicative of participants responding faster at the expense of making more errors. This condition, which should have been a comparatively easy one, yielded the numerically highest error rates. Nonetheless, this latter explanation seems unlikely, primarily because it assumes that participants selectively change the speed-accuracy tradeoff in one condition, but not in the others. There appears to be no plausible reason that justifies why participants would modify their strategy from an item to the next in the same list.

Lastly, when the object switched, an expected content-retrieval cost was observed in Experiment 2a, although this effect was not present in Experiment 2b. This last result seems somewhat atypical. The retrieval effect across all three experiments was clear, provided that object switching occurred. We do not have a satisfying explanation for this result that departs from previous findings.

General discussion

The aim of this study was to determine whether focus switching involves two separate processes: context access and content retrieval. Three experiments were carried out to analyze the effects of object switching, the requirements for retrieving its content, and the alternation of the retrieval operations. The results revealed a complex pattern in which the different factors interacted.

A main finding of the present study was that a content retrieval effect was generally found when object switching, and hence context access, was required. In the two last experiments, the content-retrieval cost was over 200 ms when the retrieval operation switched. In the same condition the object switching cost was around 300 ms. Thus, these data suggest that focus switching can be decomposed into two subprocesses: context access and content retrieval. Bringing an element into the focus of

attention may involve the processing and activation of the context and the subsequent retrieval of its content. It is also possible that the content could be retrieved in parallel to the context, but with some delay. Therefore, contexts (cues) and their contents (numerical information) may be independently accessed.

We have considered the idea that the object-switching cost reflects the cost of switching the focus of attention from one content to another. Recently, this explanation has been modified to account for a repetition cost observed in situations whereby the same item belongs to different lists (Oberauer, Souza, Druey, & Gade, 2013). From this approach, the focus of attention includes not only the content but also the context and its bindings to the content (Oberauer, 2013). Thus, the switching cost would indicate the cost of switching the focus from one context-content conjunction to another. Both views are similar in that they see content as being retrieved through its context. In this respect, the present results fit well with them.

There is not a clear explanation for the divergent effect of retrieval observed in the present study for response times and the null result reported by Bialkova and Oberauer (2010). Besides the similarities between the tasks used in both studies, a number of differences were also observed. For instance, we used a simpler task with two objects instead of three, more informative context cues (figures plus colour rather than just colour), and a reduced number of operations (± 1 , ± 2) with results ranging from 3 to 9. Some of these features could have had an impact on the object-switching cost. For instance, increasing the load from two to three also increases the switching cost (see also Oberauer, Wendland, & Kliegl, 2003). The use of more informative context cues (e.g., figures and colours) could have decreased the switching cost (see Verhaeghen et al., 2004; Verhaeghen & Basak, 2005). However, at present, we do not see how these

particular features can be responsible for the different results obtained in both studies regarding the retrieval effect.

That said, there is a feature of the task in the present study that may have contributed to faster performance when complete equations were presented. The to-be-memorized digits were always determined on the basis of the digit maintained in memory. It is possible that performance on complete equations was facilitated because the number maintained in WM was presented as the first digit of the complete equation. In the study by Bialkova and Oberauer (2010), the numbers for the complete equations were randomly selected. Therefore, any possible facilitation in the present experiment could not have occurred in the aforementioned experiment. While it remains a possibility, further research is needed to precisely account for the origin of the differences.

In addition to the general pattern reported when the object switched, other findings of particular relevance have been consistently observed in object-repetition trials. A content-retrieval cost or a content-retrieval benefit was observed depending on whether or not the retrieval operation switched.

First, when the retrieval operation switched, a retrieval effect was observed even when the object was repeated. One might initially expect a content-retrieval effect in object-switching trials, but not when the object remains the same because the information is already in the focus of attention. In fact, this retrieval cost may indicate that alternating the retrieval operation removes the advantage of maintaining the information in the focus. A tentative explanation could be that the cue for incomplete operations in these trials induces content retrieval even though it would be not necessary. In this case, the information would be reactivated again in the focus. However, if this were the case, it would still be necessary to explain why the content-

retrieval effect disappears when the retrieval operation is repeated, given that the cues for information retrieval were analogous in both conditions.

A more plausible explanation is that after encoding the task and accessing the object, the cognitive operation and the object have to be bound. Once the object and retrieval operation have been bound, the content has to be retrieved again. This is compatible with the view held by Oberauer (2009; see also Souza, Oberauer, Gade, & Druery, 2012), who claims that some bindings must be set up between the mental objects and the cognitive operations on them. From this perspective, the focus of attention, which is part of the declarative WM, would hold the object, whereas the response focus, as part of the procedural WM, would select a cognitive action. A link between the two foci is necessary for them to communicate. Each time the task or object changes, a new binding would be required. Then, once the binding has been created, the information associated with the object should be retrieved again. This might be what we observed in this condition.

A second and initially unexpected result emerged when both retrieval operation and object were repeated: a content-retrieval benefit rather than a content-retrieval cost was observed. Thus, less time was required to perform the task when the arithmetic operation was incomplete than when all the necessary information was presented on the screen. Simply put, the arithmetic operation (e.g., +1) was applied faster to an operand held in the focus (e.g., 3) than to an operand also displayed on the screen (e.g., 3+1).

When the object was repeated, we anticipated that the content-retrieval cost would disappear, given that there was no need to access its content because it was already in the focus. However, rather than finding a reduction or elimination of the content-retrieval cost, a considerable time benefit was observed. This pattern, one we had not expected in the first experiment, was confirmed by two additional experiments.

It could be argued that, in the latter case, the first operand must be coded and activated in the focus of attention, a step that is not necessary in the first case. Therefore, when both the first operand and the retrieval operation are in the focus, the arithmetic operation can be performed faster. If the effect of retrieval operation alternation had not been taken into account in this study, the content-retrieval costs and benefits in the object-repetition trials would have been compensated. As a result, this effect would be absent or rather limited.

This study has shown that focus switching involves context retrieval and content access as two different components. Other processes may also contribute to focus switching. For instance, Gehring et al. (2003) have shown that cue priming may account for around a third of the switching cost. Other approaches may prove valuable to better understand focus switching. Along these lines, Hedge and Leonard (2013) have used a spatial updating task to study focus switching by considering Posner's attentional model (Posner, 2008). These authors have concluded that part of the switching cost is related to the disengagement of attention to the initial object, and at least a third of the switching cost is due to an increase in the dwell time on the updated object. However, it remains to be determined whether such processes also play a role in focus switching on verbal WM tasks.

To conclude, focus switching in WM may be understood as a content-addressable retrieval process. Objects in WM are made up of contents and context representations (e.g., serial positions, contextual time information, external stimuli) that must be bound at the moment of encoding. The activation of a content in the focus of attention requires the previous activation of its context. This reflects a common retrieval mechanism contemplated in numerous models of WM (Brown, Preece, & Hulme, 2000;

Burgess & Hitch, 1999; McElree, 2006; Nairne, 2002; Oberauer, 2013; Oberauer, Lewandowsky, Farrell, Jarrold, & Greaves, 2012).

Furthermore, when a cognitive operation has to be applied to an object, it is necessary to bind the object and the operation (Oberauer, 2009; Souza et al., 2012). This binding would need to be set up whenever a cognitive action or object switches. The content associated to an object can be retrieved only after such a binding has been established.

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Table 1.

ANOVA results for Experiments 1, 2a and 2b.

	Experiment 1				Experiment 2a				Experiment 2b							
	<i>RT</i>				<i>RT</i>				<i>RT</i>				<i>ACC</i>			
	<i>F</i>	<i>df</i>	<i>p</i>	η_p^2	<i>F</i>	<i>df</i>	<i>p</i>	η_p^2	<i>F</i>	<i>df</i>	<i>p</i>	η_p^2	<i>F</i>	<i>df</i>	<i>p</i>	η_p^2
Retrieval op. alter.*	33.64	1, 22	<.001	.61	49.92	1, 21	<.001	.70	34.05	1, 23	<.001	.60	5.59	1, 23	.027	.20
Object sw.	68.38	1, 22	<.001	.76	21.96	1, 21	<.001	.51	40.76	1, 23	<.001	.64	10.52	1, 23	.004	.31
Content retr.	5.31	1, 22	.031	.19	4.35	1, 21	.049	.17	1.26	1, 23	.273	.05	29.42	1, 23	<.001	.56
Retrieval op. alter. x Object sw.	5.11	1, 22	.034	.19	13.81	1, 21	<.001	.40	19.45	1, 23	<.001	.46	5.26	1, 23	.031	.19
Retrieval op. alter. x Content retr.	3.25	1, 22	.085	.13	10.45	1, 21	.004	.33	30.83	1, 23	<.001	.57	13.83	1, 23	<.001	.38
Object sw. x Content retr.	38.94	1, 22	<.001	.64	27.23	1, 21	<.001	.57	14.84	1, 23	.001	.39	0.00	1, 23	.982	.00
Object sw. x Content retr. x Retrieval op. alter.	11.44	1, 22	.003	.34	5.27	1, 21	.032	.20	5.23	1, 23	.032	.19	6.16	1, 23	.021	.21
Retrieval op. repetition																
Object sw.	88.06	1, 22	<.001	.80	29.62	1, 21	<.001	.59	47.20	1, 23	<.001	.67	0.01	1, 23	.913	.00
Content retr.	0.23	1, 22	.634	.01	0.16	1, 21	.694	.01	8.66	1, 23	.010	.27	34.94	1, 23	<.001	.60
Object sw. x Content retr.	50.87	1, 22	<.001	.70	29.04	1, 21	.010	.58	21.14	1, 23	<.001	.48	2.90	1, 23	.102	.11
Retrieval op. switch																
Object sw.	25.03	1, 22	<.001	.53	8.16	1, 21	.009	.28	25.78	1, 23	<.001	.53	11.04	1, 23	.003	.32
Content retr.	9.18	1, 22	.006	.29	10.21	1, 21	.004	.33	10.11	1, 23	.004	.31	19.18	1, 23	<.001	.46
Object sw. x Content retr.	6.53	1, 22	.018	.23	3.34	1, 21	.082	.14	0.260	1, 23	.615	.01	2.24	1, 23	.148	.09

Note. Retrieval op. alter.: Retrieval operation alternation; Object sw.: Object switching; Content retr.: Content retrieval

*In Experiment 1, Retrieval operation alternation was manipulated between lists (single vs. mixed). Single lists comprised only one type of retrieval operation, whereas mixed lists included both types of retrieval operations. See the main text for further explanation.

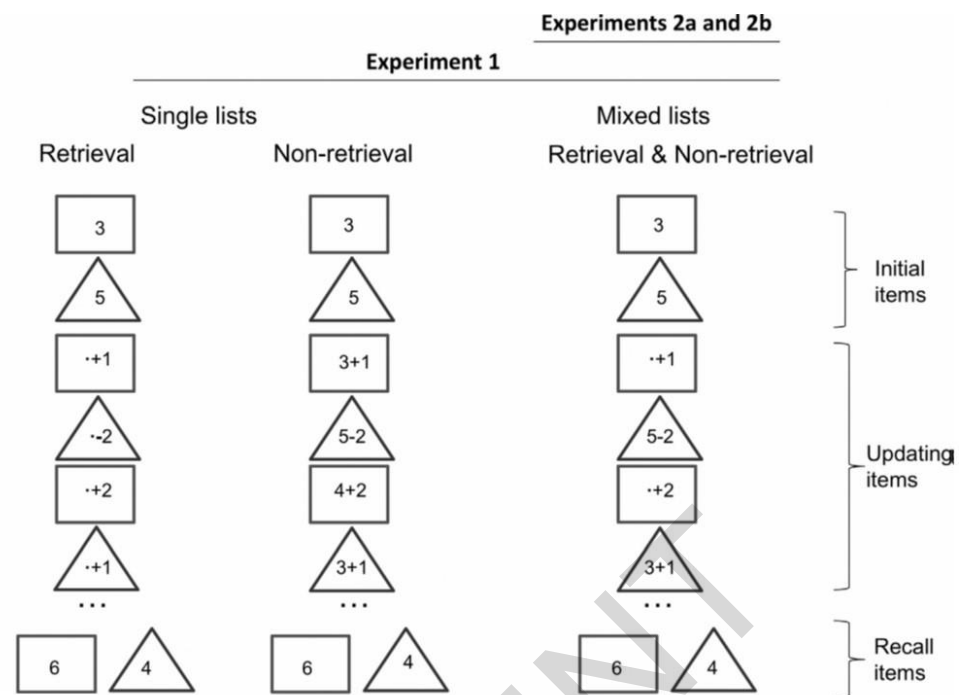


Figure 1. Representation of an example sequence for each experiment.

Experiment 1 included single lists (with retrieval or non-retrieval operations) and mixed lists (with both retrieval operations). Experiments 2a and 2b used only mixed lists. Each list comprised two initial items and a variable number of updating items made up of arithmetic operations displayed inside two coloured figures (blue triangles and red squares). At the end of the list, a recall request for each figure was presented.

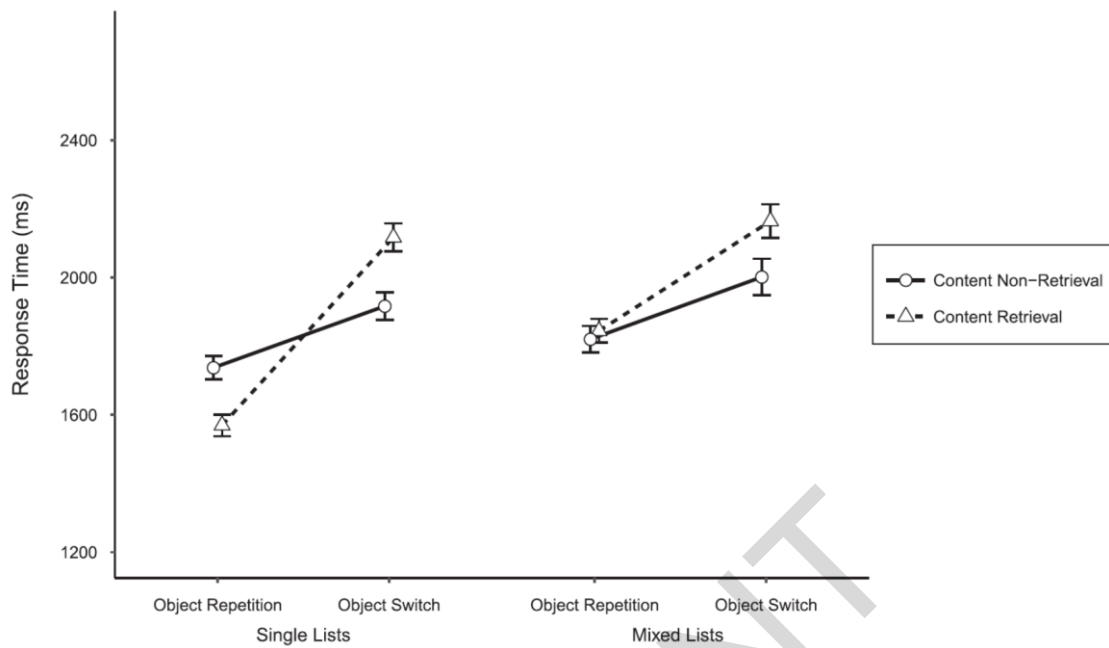


Figure 2. Mean RTs (ms) in Experiment 1 as a function of object switching, content retrieval and retrieval operation alternation. Error bars represent one standard error of the mean. In the single lists, all items involved retrieval operation repetitions. In the mixed lists, items with retrieval operation switches featured alongside items with repeated retrieval operations.

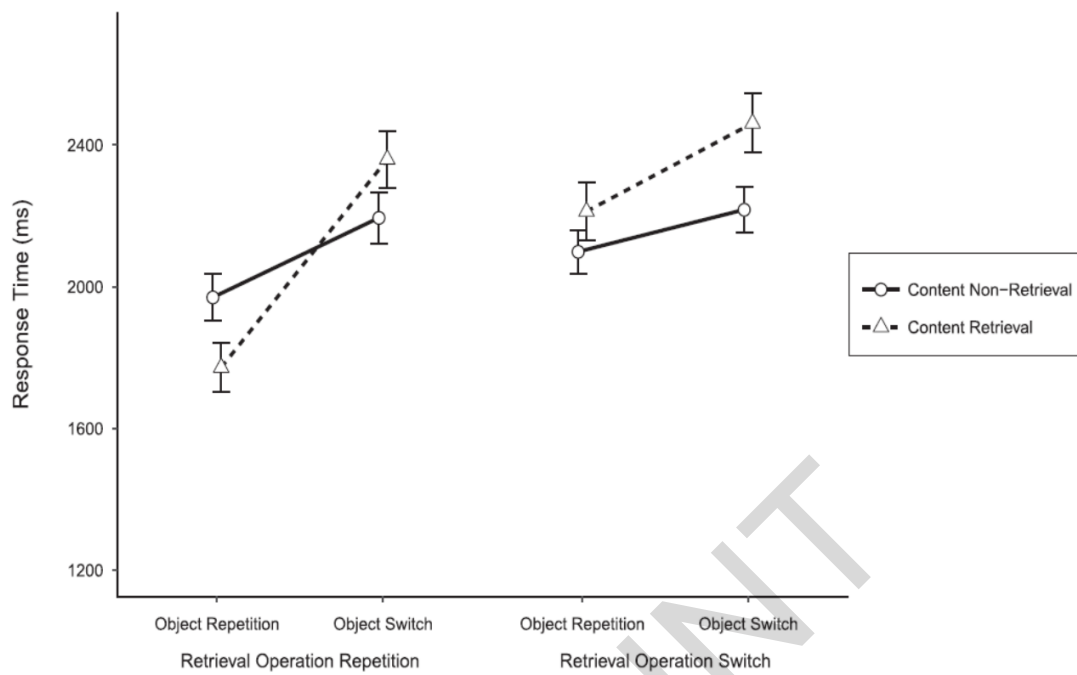


Figure 3. Mean RTs (ms) in Experiment 2a as a function of object switching, content retrieval and retrieval operation alternation. Error bars represent one standard error of the mean.

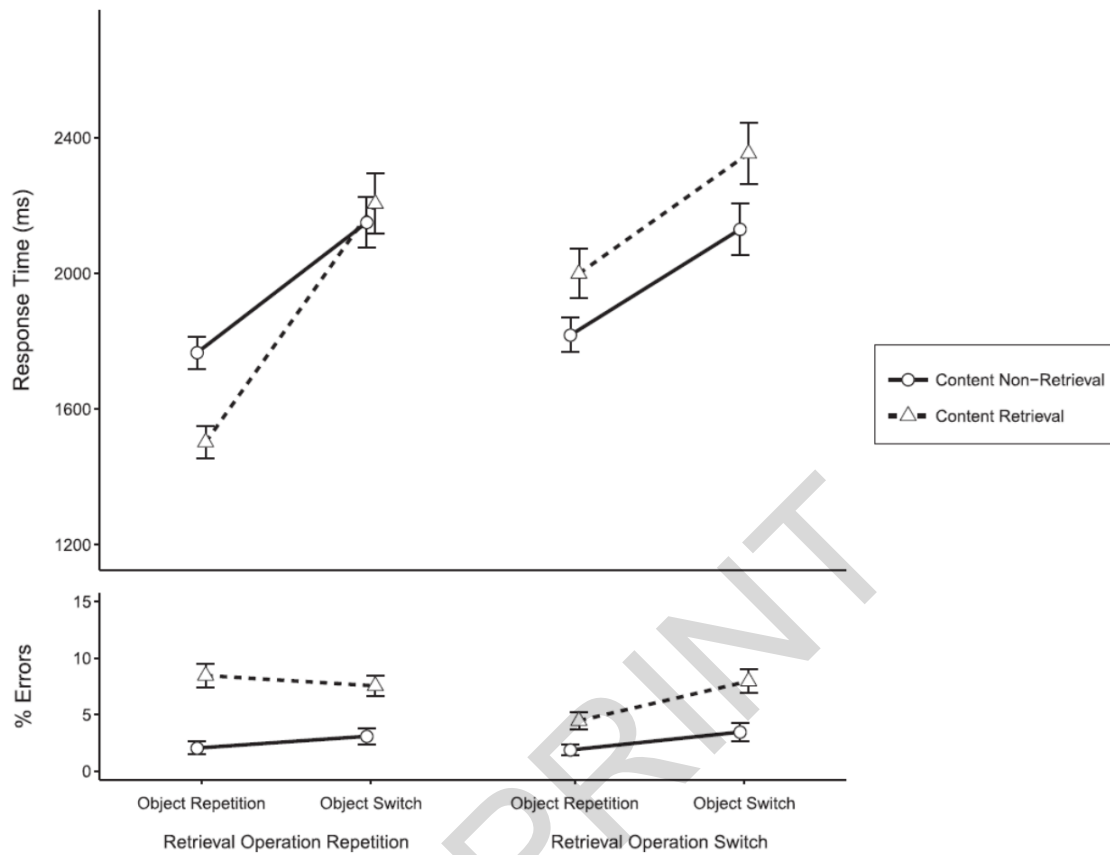


Figure 4. Mean RTs (ms) and error rates (%) in Experiment 2b as a function of object switching, content retrieval and retrieval operation alternation. Error bars represent one standard error of the mean.