# Evading a Multitasking Bottleneck: Presenting Intermediate Representations in the Environment

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**Abstract**

When people have to store intermediate results for multiple tasks concurrently, performance decreases considerably as opposed to when at most one intermediate result has to be stored. Borst, Taatgen and Van Rijn (2010) have shown that a multitasking bottleneck associated with intermediate problem representations can account for this effect. This study investigates whether representing problem representations externally reduces the interference. To this end we extended the experiment in Borst et al. (2010) with a version that required no problem representation. The results show that there is an over-additive increase in response times when both tasks need to store an intermediate representation, as compared to a situation in which at most one task requires an intermediate representation, either because no intermediate representation is needed, or because the intermediate representation is available on the screen. These results suggest that multitasking performance can be improved by presenting intermediate representations in the environment.

**Keywords:** multitasking; interference; problem state; external representation; threaded cognition.

## Introduction

When you walk through the city on a Saturday afternoon you come across many examples of multitasking: Business men who are trying to talk on the phone while driving, tourists reading a map while walking, and boys watching girls while riding their bikes. These are examples of the ability of human beings to do several tasks at once. While this capability works effortless in certain situations, like walking and talking, other examples suggest it is nearly impossible to execute two tasks at once (e.g., writing a paper and watching television). Here we discuss multitasking interference in the *problem state* resource, which can be considered part of working memory, and how to avoid it.

There are several theories that discuss multitasking interference (e.g., Pashler, 1984; Meyer & Kieras, 1997; Salvucci & Taatgen, 2008). These theories differ in their explanation of what causes interference during multitasking: ranging from one central processing bottleneck (e.g., Pashler, 1984) to a purely cognitive control account (e.g., Meyer & Kieras, 1997) The theory of threaded cognition (Salvucci & Taatgen, 2008; Salvucci, Taatgen, & Borst, 2009) takes the middle ground by assuming multiple processing bottlenecks, both cognitive and perceptual. According to threaded cognition human multitasking is not limited by the number of tasks that are carried out, but by capacity limitations of cognitive and peripheral resources. As soon as a resource is required by more than one task, this leads to interference.

Previously Salvucci and Taatgen (2008) discussed two peripheral bottlenecks (the visual and motor systems) and two central cognitive bottlenecks (declarative and procedural memory; cf. "attentional limitations" Pashler & Johnston, 1998). A third central cognitive resource that can act as a bottleneck, the problem state resource, was identified by Borst, Taatgen and Van Rijn (2010). The problem state is the cognitive resource that holds intermediate results of processing. While solving an equation like $3x - 4 = 8$, a likely intermediate representation that is stored in the problem state is $3x = 12$.

According to threaded cognition, a resource can only be used for one task at a time, which means that the problem state resource can only store a single intermediate representation. Intermediate representations that are removed from the problem state resource are automatically stored in declarative memory. The distinction between the problem state resource on the one hand, and declarative memory on the other hand is an important one: Information that is represented in the problem state resource is directly accessible, while retrieving facts from declarative memory costs time.

The idea of a problem state is similar to the focus of attention in working memory (e.g., Cowan, 1995; Garavan, 1998; Oberauer, 2002) in the sense that it has a size of only one element and can be accessed without time costs. Changing from one problem state to another takes a small amount of time (previously estimated to be around 200 ms, Anderson, 2007). Moreover, when a previous problem state has to be retrieved from declarative memory this increases the time it takes to change the problem state.

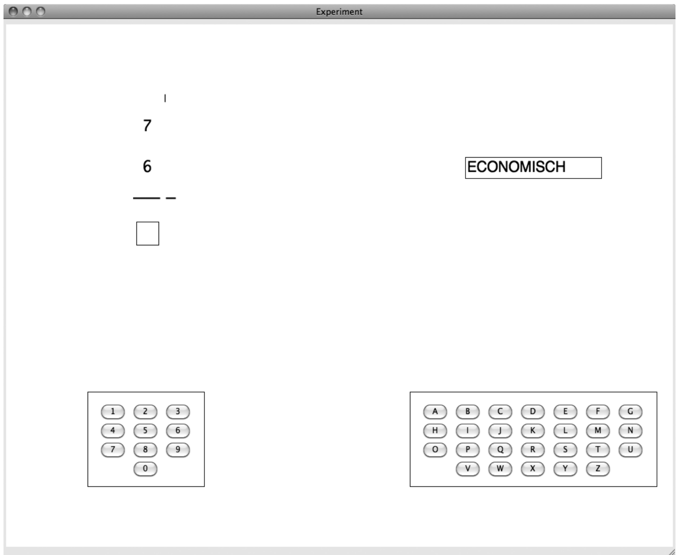


Figure 1: A screenshot of the experiment in the support condition.

Borst et al. (2010) showed that the problem state acts as a cognitive bottleneck in multitasking using a dual task experiment in which both tasks varied in whether they needed a problem state or not. They found an over-additive interaction effect on reaction times and accuracy when both tasks needed a problem state.

If interference in the problem state produces such a large decrease in performance, people will try to find ways to avoid it. This is consistent with the minimal control principle, which proposes that internal top-down control should be minimized to obtain the best performance with the least cognitive processing (Taatgen, 2007). This means that whenever possible, control is left to the environment. Taatgen showed that control is not fully internal, but is shared by perceptual input and internal top-down control.

We hypothesize that people use their environment to relieve their problem state whenever possible (e.g., Kirsh, 1995). To test this claim we used a modified version of the dual task experiment from Borst et al. (2010). In that experiment, participants had to perform two tasks concurrently: a subtraction task and a text entry task. Both tasks had two conditions: an easy version in which no intermediate results had to be stored, and a hard version in which participants had to maintain an intermediate result from one response to the next. We extended this setup with a version of the task in which the problem state for the subtraction task is displayed on the screen. Kirsh (1995) shows that people can pass off internal computation to the world by correctly timed external representations. In this version of the task we implemented this idea by presenting an external representation of the intermediate outcome when it was needed for further computation. Because the intermediate outcome was presented on the screen, it was not necessary to maintain a problem state in the hard version of the subtraction task. This version of the task will be referred to as the 'support condition', while the original version will be referred to as the 'no-support condition'.

In the no-support condition, we expected to find an interaction between task difficulty, in both response times and accuracy, similar to the interaction found in the original study. In the support condition, it is not necessary to maintain two problem states concurrently; therefore we expect to find that participants respond faster and more accurate when both tasks are hard. Therefore, we expect the interaction effect to decrease or disappear.

## Method

The experiment is derived from a dual task that was previously used to provide support for the problem state bottleneck hypothesis (Borst et al., 2010). We extended this original version with a version of the task in which the intermediate result of the subtraction task is displayed on the screen. The experiment has a 2 x 2 x 2 factorial within-subject design (Subtraction Difficulty x Text Entry Difficulty x support). Eye-movements of the participants were measured during the experiment, but here we will focus on the behavioral data.

**Participants** 33 students of the University of Groningen participated in the experiment for course credit or monetary compensation of €10. 4 participants were rejected because they scored less than 75% correct where the average of the other participants was >95% correct (as were the results on the same task in Borst, Taatgen, Stocco et al. 2010 and in Borst, Taatgen, & Van Rijn, 2010). Two participants were rejected because they did not adhere to the task instructions, and 4 because of recording problems of the eye tracker[1]. This leaves 24 complete datasets (16 female, age range 18-43, mean age 20.5). All participants had normal or corrected-to-normal visual acuity. Informed consent as approved by the Ethical Committee Psychology of the University of Groningen was obtained before testing.

**Design** During the experiment, participants had to perform a subtraction task and a text entry task concurrently. The subtraction task was shown on the left side of the screen, the text entry task on the right (see Figure 1). Participants had to alternate between the two tasks: after entering a digit, the subtraction interface was disabled, forcing the participant to subsequently enter a letter. After entering a letter, the text entry interface was disabled and the subtraction interface became available again, etc.

The subtraction task is shown on the left side of Figure 1. Participants had to solve 10-column subtraction problems in standard right to left order. However, at each point in time, only a single column was visible. Although the problems were presented column by column, the participants were trained to perceive the separate columns in a trial as one 10-column subtraction problem (in the practice phase

[1] We chose to exclude these participants from the current analysis to keep the data set the same as in future analyses. Including or excluding these participants did not qualitatively influence the reported behavioral effects.

participants started out with a normal 10-column layout, only later they switched to solving the problems column by column). Participants had to enter the digits by clicking on the on-screen keypad with the mouse. In the easy, no problem state version, the upper digit was always larger or equal to the lower one; these problems could be solved without carrying. In contrast, the hard version required participants to carry six times out of 10 possible columns.

The interface for the text entry task is shown on the right in Figure 1. Participants had to enter 10-letter strings by clicking on the on-screen keypad. In the easy version the input strings were presented one letter at a time and participants had to click the corresponding button on the keypad. In the hard version, a 10-letter word was presented once at the start of a trial. Once a participant clicked on the first letter, the word disappeared and the remaining letters had to be entered one at a time, without feedback. Thus, after the initial presentation of the word in the hard condition, participants could neither see what word they were entering, nor what they had already entered.

In the support condition a marker on the screen indicated whether a carry was in progress in the subtraction task. Figure 1 shows this condition. The '|' indicates that there is currently no carry in progress. However, as soon as the previous subtraction resulted in a carry (e.g., after a column like 3 – 4), the '|' turned into a '1'. These symbols were chosen so that it was not possible to distinguish the two characters in peripheral vision.

**Stimuli and Apparatus** The stimuli for the subtraction task were generated anew for each participant. The subtraction problems in the hard version always featured six carries, and resulted in 10-digit answers. The 10 letter words for the hard version of the text entry task were handpicked from a list of high-frequency English words (CELEX database; Baayen, Piepenbrock, & van Rijn, 1993) to ensure that similarities between words were kept at a minimum. These stimuli were also used in the easy text entry task, except that the letters within the words were scrambled (under the constraint that a letter never appeared twice in a row). Thus, participants were presented pseudo-random sequences of letters that they had to enter one-by-one in the easy condition. By scrambling the words, we controlled for letter-based effects, while preventing the use of strategies to predict the next letter.

The experiment was presented full screen on a 20.1" monitor.

**Procedure** Each trial started with the presentation of a short eye tracker calibration circle, followed by a fixation cross that was presented for 6 seconds. The fixation marker was followed by two horizontally aligned colored circles representing both tasks. The color of the circles indicated the difficulty conditions of the two tasks in the next trial (red for hard, green for easy). The circles stayed on the screen for 1 second, followed by a fixation cross for 600 ms after which the subtraction and text entry tasks appeared. Participants had to begin with the subtraction task, and then alternate between the two tasks. After completing both tasks, a feedback screen was shown for 2 seconds, indicating how many letters / digits were entered correctly. Before the next trial started, a fixation screen was shown for 2 seconds.

The experiment consisted of a practice block and two experimental blocks. One of the experimental blocks contained the support condition; the order of the conditions was counter-balanced over participants. The practice block consisted of 12 single task trials, followed by a block of 4 multitask trials in which all combinations of subtraction and text entry were presented (easy-easy, hard-easy, easy-hard, and hard-hard). Both experimental blocks consisted of 28 multitask trials. Before the second block the subtraction task was practiced again, to familiarize the participants with the change caused by adding or removing the carry indicator. Subtraction and text entry conditions were randomized within a block. The complete experiment consisted of 56 experimental trials, and lasted for about 90 minutes. In between blocks participants could take a short break.

## Results

Only the data from the experimental phase were analyzed. Outliers were removed from the data (Response Times < 250 ms or > 10,000 ms), after which we removed data exceeding two standard deviations from the mean per condition per participant (in total 2.2% of the data was removed).

All *F*- and *p*-values are obtained from repeated measure ANOVAs; all error bars depict standard errors. Accuracy data was transformed using an arcsine transformation before being submitted to the ANOVA.

### Response Times

Response times on the text entry task are defined as the time between entering the previous number and the current letter. First responses of each trial were removed. The results for the text entry task are shown in the upper panels of Figure 2. In summary: we found an interaction effect between Subtraction Difficulty and Text Entry Difficulty in both the no-support and the support condition, but in the support condition this interaction is much smaller.

First, we found a three-way interaction between Subtraction Difficulty, Text Entry Difficulty and Support ($F(1,23) = 9.29$, $p = 0.01$, $\eta_p^2 = 0.29$). This indicates that the interaction between Subtraction Difficulty and Text Entry difficulty differed based on whether support was displayed on the screen.

The ANOVA results for the different conditions are summarized in Table 1. There is an interaction effect between Subtraction Difficulty and Text Entry Difficulty and a main effect of Subtraction Difficulty in the normal condition. No main effect of Text Entry Difficulty was found. For the support condition of the task we found an interaction between Subtraction Difficulty and Text Entry Difficulty and a main effect of Subtraction Difficulty. No main effect of Text Entry Difficulty was found.

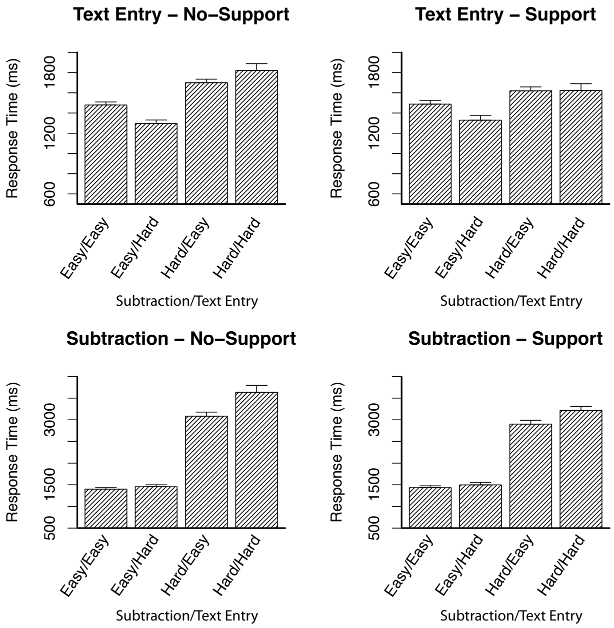


Figure 2: Response Times (ms) on both tasks. displayed on the screen.

While there is an interaction effect present in both the support and the no-support condition, the three-way interaction shows that the interaction is smaller in the no-support condition. This could indicate that adding the external support alleviates the problem state.

Response times on the subtraction task are defined as the time between clicking on a letter in the text entry task and clicking on a number in the subtraction task. First responses of each trial were removed. The results for the subtraction task are shown in the lower panels of Figure 2. In both conditions there seems to be an interaction, but in the support condition this interaction is smaller: We found a three-way interaction between Subtraction Difficulty, Text Entry, and Support ($F(1,23) = 5.05$, $p = 0.03$, $\eta_p^2 = 0.18$) on the subtraction task. Further ANOVA results are summarized in Table 2.

Table 1: ANOVA results for the response times on the text entry task.

| **RT - Text Entry - No-Support** | ***F*(1,23)** | ***p*** | $\eta_p^2$ |
|---|---|---|---|
| Subtraction Difficulty x Text Entry Difficulty | 26.45 | < 0.01 | 0.53 |
| Subtraction Difficulty | 133.64 | < 0.01 | 0.85 |
| Text Entry Difficulty | < 1 | - | 0.01 |

| **RT - Text Entry - Support** | ***F*(1,23)** | ***p*** | $\eta_p^2$ |
|---|---|---|---|
| Subtraction Difficulty x Text Entry Difficulty | 8.60 | < 0.01 | 0.27 |
| Subtraction Difficulty | 46.42 | < 0.01 | 0.67 |
| Text Entry Difficulty | 2.65 | > 0.1 | 0.10 |

Table 2: ANOVA results for the response times on the subtraction task.

| **RT - Subtraction - No-Support** | ***F*(1,23)** | ***p*** | $\eta_p^2$ |
|---|---|---|---|
| Subtraction Difficulty x Text Entry Difficulty | 20.01 | < 0.01 | 0.47 |
| Subtraction Difficulty | 357.9 | < 0.01 | 0.94 |
| Text Entry Difficulty | 22.04 | <0.01 | 0.49 |

| **RT - Subtraction - Support** | ***F*(1,23)** | ***p*** | $\eta_p^2$ |
|---|---|---|---|
| Subtraction Difficulty x Text Entry Difficulty | 14.52 | < 0.01 | 0.39 |
| Subtraction Difficulty | 531.33 | < 0.01 | 0.96 |
| Text Entry Difficulty | 15.04 | < 0.01 | 0.40 |

In the normal condition, an interaction effect between Subtraction Difficulty and Text Entry Difficulty was found. This interaction replicates the effects reported by Borst, Taatgen and Van Rijn (2010). There were main effects for both Subtraction Difficulty and Text Entry Difficulty. In the support condition we found an interaction between Subtraction Difficulty and Text Entry Difficulty, but this interaction was significantly smaller than the interaction in the no-support version. This indicates that representing the problem state on the screen decreases interference in the problem state.

Both tasks show a decreased interaction in the support condition, which indicates that displaying an intermediate representation externally reduces interference in the problem state resource.

## Accuracy

Accuracy is defined as the percentage correctly entered responses. First responses of each trial were removed.

The upper panels of Figure 3 show the results for the text entry task. In both conditions an interaction is present, but this interaction becomes smaller when support is added.

For the text entry task no three-way interaction was found ($F(1,23) = 1.07$, $p > 0.1$, $\eta_p^2 = 0.04$), further ANOVA results are summarize in Table 3. This means that adding external support did not influence accuracy on the text entry task.

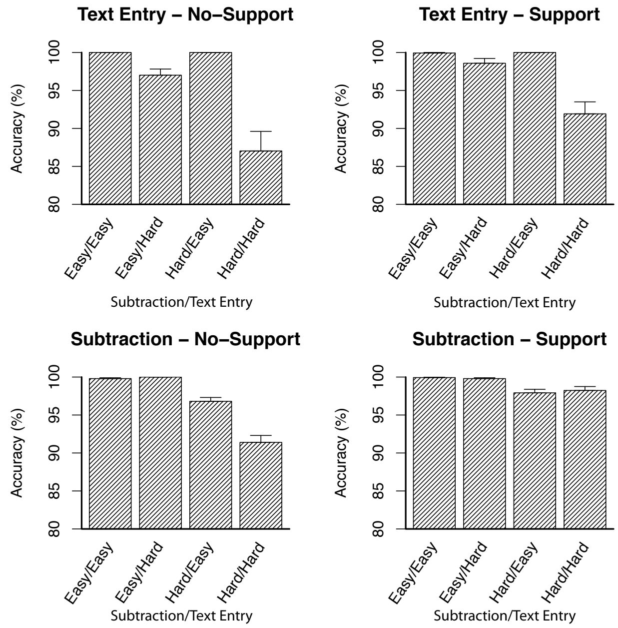


Figure 3: Accuracy in percentage correct answers on both tasks.

The accuracy on the text entry task is shown in the upper panels of Figure 3. In both the support and no-support condition an interaction between Subtraction Difficulty and Text Entry Difficulty was found.

The results for the subtraction task are shown in the lower panels of Figure 3. The interaction effect, that is present in the normal condition, has disappeared in the support condition.

Table 3: ANOVA results for the accuracy on the Text Entry task

| **Acc - Text Entry - No-Support** | ***F*(1,23)** | ***p*** | **$\eta_p^2$** |
|---|---|---|---|
| Subtraction Difficulty x Text Entry Difficulty | 28.1 | < 0.001 | 0.55 |
| Subtraction Difficulty | 25.9 | < 0.001 | 0.53 |
| Text Entry Difficulty | 173.0 | < 0.001 | 0.88 |

| **Acc - Text Entry - Support** | ***F*(1,23)** | ***p*** | **$\eta_p^2$** |
|---|---|---|---|
| Subtraction Difficulty x Text Entry Difficulty | 20.09 | < 0.01 | 0.47 |
| Subtraction Difficulty | 18.82 | < 0.01 | 0.45 |
| Text Entry Difficulty | 25.12 | < 0.01 | 0.52 |

Table 4: ANOVA results for the accuracy on the Subtraction task.

| **Acc - Subtraction - No-Support** | ***F*(1,23)** | ***p*** | **$\eta_p^2$** |
|---|---|---|---|
| Subtraction Difficulty x Text Entry Difficulty | 58.2 | < 0.01 | 0.72 |
| Subtraction Difficulty | 80.36 | < 0.01 | 0.77 |
| Text Entry Difficulty | 45.0 | < 0.01 | 0.66 |

| **Acc - Subtraction - Support** | ***F*(1,23)** | ***p*** | **$\eta_p^2$** |
|---|---|---|---|
| Subtraction Difficulty x Text Entry Difficulty | 1.11 | > 0.1 | 0.05 |
| Subtraction Difficulty | 36.8 | < 0.001 | 0.62 |
| Text Entry Difficulty | < 1 | - | < 0.01 |

On the subtraction task we found a significant three-way interaction between Subtraction Difficulty, Text Entry Difficulty and Support ($F(1,23) = 21.41$, $p < 0.01$, $\eta_p^2 = 0.48$), which shows that there is a difference between the interaction of Subtraction Difficulty and Text Entry Difficulty with respect to support. Further ANOVA results are summarized in Table 4. There is an interaction between Subtraction Difficulty and Text Entry Difficulty and there are main effects of Subtraction Difficulty and Text Entry Difficulty. The upper right panel of Figure 3 shows the accuracy on the text entry task in the support condition.

The interaction effect that was present in the condition without support is not present in the condition with support. This indicates that while adding external support for the problem state did not influence the accuracy on the text entry task, the interference that was present in the subtraction task without support disappeared when the support was displayed.

## Discussion

We have investigated if people use their environment to evade the interference that arises when two tasks concurrently need to maintain an intermediate result. Hereto, we presented an external representation of the intermediate result of the task on the screen.

The findings presented here show interactions between Subtraction Difficulty and Text Entry Difficulty in the no-support condition in both response times and accuracy. This effect was predicted because a bottleneck occurs when two tasks concurrently need to maintain a problem state (Borst et al., 2010). In addition, the support condition demonstrates that displaying an external representation of the problem state improves performance on the tasks, not only in the subtraction task (where the support was implemented) but also in the text entry task. In line with the ideas of the minimal control principle (Taatgen, 2007), which showed that cognitive control is shared between perceptual input and internal cognition, we have shown that this could be the case for maintaining intermediate representations.

Although these results indicate that the external representation does indeed take over part of the role of the problem state resource and thereby reduces interference, we expected to find a complete absence of an interaction effect in both response times and accuracy of the subtraction task. However, while the interaction effect in the accuracy data indeed disappeared, the interaction in the response decreased, but is still present. For the subtraction task this can be explained by the time it takes to look at the supporting symbol on the screen: the time it previously took to recall the problem state from memory is now used to look at the supporting symbol. However, this does not take into account that there still is an interaction effect in the text entry data.

A more plausible explanation is that at least some participants still store a representation of the subtraction task in their problem state. During the text entry task this representation is replaced by the representation of the text entry task. When returning to the subtraction task, the problem state does not have to be recalled from declarative memory and because the support on the screen is always correct it is more accurate. This explanation can also account for the interaction in the response times for the text entry data. Because there still is a problem state for the subtraction task, this problem state has to be exchanged for the problem state of the text entry task. Thus, while participants did not need a problem state to perform the task, they still seem to create one. Although it seems clear that participants use their environment to relieve the interference in the problem state, it seems like they initially still create a problem state for the subtraction task. The current experiment does not provide a sufficient explanation for what happens exactly in the problem state. Future research could therefore focus on letting participants themselves construct a representation of the problem state in the environment. In the current experiment the representation of the intermediate result is always displayed on the screen, whether a participant needs it or not. The costs for checking whether the internal problem state corresponds with the external problem representation are relatively low. In many cognitive tasks, such as solving algebra equations with pencil and paper, shopping with a shopping list and taking notes while reading a paper, external representations are created by the person who executes the task (Kirsh, 1995). Constructing your own representation would probably have a considerably higher cost, but could be more efficiently adjusted to fit the individual's needs. Due to the higher costs a self-constructed representation would only be used when necessary, it would therefore give a better understanding of when it is necessary to have an external representation as opposed to an internal problem state.

Nevertheless, externally representing intermediate results of a task can prevent interference in the problem state resource. Hereby, one of the bottlenecks that keep us from efficient multitasking can be circumvented.

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