The resource-availability model of distraction and mind-wandering

Taatgen, Niels A.; van Vugt, Marieke K.; Daamen, Jeroen; Katidioti, Ioanna; Huijser, Stefan; Borst, Jelmer P.

Published in:
Cognitive Systems Research

DOI:
10.1016/j.cogsys.2021.03.001

Available online at www.sciencedirect.com

ScienceDirect

Cognitive Systems Research 68 (2021) 84–104

Cognitive Systems RESEARCH

www.elsevier.com/locate/cogsys

The resource-availability model of distraction and mind-wandering

Niels A. Taatgen *, Marieke K. van Vugt, Jeroen Daamen, Ioanna Katidioti, Stefan Huijser, Jelmer P. Borst

University of Groningen, Bernoulli Institute for Mathematics, Computer Science and Artificial Intelligence, the Netherlands

Received 17 June 2019; received in revised form 23 September 2020; accepted 20 March 2021
Available online 5 April 2021

Abstract

This article presents a cognitive model of distraction and mind-wandering that combines and formalizes several existing theories. It assumes that task-related goals and opportunities for distraction are continuously in competition for mental resources. If the task-related goal does not need a particular resource at a particular moment, the likelihood that it is captured by a distraction is high. We applied this model to explain the results of three distraction experiments that differ from each other in a number of ways. The first experiment is a slow-paced mind-wandering study; the main result is that less mind-wandering occurs if subjects have to maintain an item in working memory. The second experiment is a working memory task in which mind-wandering is triggered by the presence of self-referential words in a secondary task; these words increase mental elaboration and reduce memory performance. The third experiment is a mental arithmetic/ memory/visual attention task, in which subjects became more distracted by a flanking (irrelevant) video as the task increased in complexity: as subjects need more time to think, they leave the visual resource vulnerable to distraction. Although these phenomena have been treated separately in the literature, we show that these phenomena can be explained by a single comprehensive model that is based on the assumption that distractions target unused cognitive resources.

Keywords: Multitasking; Mind-wandering; Cognitive modeling; Distraction

1. The Resource-availability model of distraction and Mind-wandering

In modern society, many of us struggle when dealing with distractions and competing tasks. Visual and auditory intrusions, e.g., from cell phones or tablets, are abundant and vie for attention, even if we are not really willing to give it. But even without external cues, our minds can be distracted by our own thoughts, memories, and to-do lists.

The central theory in this article is that distraction is triggered by the combination of unused cognitive resources and a distraction that targets these resources. We provide a simulation model of this theory and demonstrate that different forms of distraction and mind-wandering can be captured by a small set of principles, and we support this idea with experimental data. In particular, we predict under which circumstances distraction is more prevalent than others. We will first outline the model, and then demonstrate its relevance to three different experiments, one of mind-wandering, one of distraction through self-referential processing, and one of visual distraction.

* Corresponding author.
E-mail address: n.a.taatgen@rug.nl (N.A. Taatgen).

https://doi.org/10.1016/j.cogsys.2021.03.001
1389-0417/

1.1. Distraction and mind wandering

Distraction is studied in several domains, and distraction is defined and measured slightly differently in each. Common to all, however, is the presence of a main task and one or more distractions. Distractions can be other tasks that have secondary priority, external stimuli, and unrelated thought processes.

A first domain is multitasking. In multitasking, people do several tasks at the same time, or alternate between tasks. Research into multitasking aims to uncover the reasons behind people's decisions to engage in multitasking, either by taking on a second task or by suspending the main task to switch to a secondary task. The secondary task is not necessarily a distraction, but it often is. A well-studied example is driver distraction (Nijboer, Borst, van Rijn, & Taatgen, 2016; Salvucci & Macuga, 2002; Strayer & Johnston, 2001). In that paradigm, a secondary task is typically performed in parallel with driving, while driving still has priority. Secondary tasks may lead to a decrease in driving performance, even if the secondary task does not involve looking away from the road. Distraction in the context of multitasking can also be voluntary, such as when someone decides to take a break from a task to check their cell-phone (Katidioti, Borst, Van Vugt, & Taatgen, 2016).

A second type of distraction occurs when external stimuli that are not explicitly related to a task are presented alongside it. Despite their irrelevance, they disrupt performance (Lavie, 2005). This captures several everyday life situations. For example, it is harder to carry out a conversation in a sports bar if there are TV monitors all around you – even mute ones – and it is more difficult to read a novel when people around you are talking.

The third type of distraction is mind-wandering, which has no direct connection to a person's current goals or environment (Smallwood & Schooler, 2015) and is therefore frequently defined as "task-unrelated thinking" (Giambra, 1989). This type of distraction can only be measured indirectly, for example by means of "thought probes", questions embedded in the task that ask the subject whether they were paying attention to the task or to something else (Smallwood & Schooler, 2006). It has been found that mind-wandering measured in this way is associated with increases in the variability of response time (e.g., Bastian & Sackur, 2013), and impairments in task performance (e.g., reading comprehension, Dixon & Bortolussi, 2013; Franklin, Smallwood, & Schooler, 2011).

The assumption of the cognitive model presented in this article is that there is no fundamental distinction between the three forms of distraction, because each of them involves a mental competition between things that can be done next. The model applies the same principles and mechanisms to simulate all three. As a consequence, visual distraction, which is easy to measure, should be able to also tell us something about mental distraction and mind-wandering. This is in line with findings of Forster and Lavie who showed correlations between a person's susceptibility to distractor interference and their tendency to mind-wander (Forster & Lavie, 2014). We will show that a model based on this assumption can indeed account for classical mind-wandering in both simple and more complex tasks, as well as for typical visual distractions.

2. Theories of distraction

Theories of multitasking typically do not focus on distraction, but describe how cognition handles parallel processing of multiple tasks, which includes the assignment of priorities to different tasks, and the extent to which the tasks interfere. Most existing theories agree that an explanation for multitasking involves the sharing of mental resources (Wickens, 2002, 2008). Theories differ in how control is organized and which resources are bottlenecks. The EPIC theory (Meyer & Kieras, 1997) assumes central cognitive resources can be shared by multiple tasks, and control involves task-specific strategies. Interference can be attributed to either a peripheral resource that cannot be shared, or a suboptimal control strategy. The threaded cognition theory, which is based on ACT-R (Salvucci & Taatgen, 2008), assumes none of the resources can be shared among tasks, and that control is performed by a simple greedy first-come-first-served strategy. A possible consequence of the threaded cognition view of multitasking is that a distraction can only be "successful" if it targets an available resource (Hockey, 1997, Katidioti & Taatgen, 2014). Although the greedy strategy works well in typical asynchronous situations, it is often necessary to make decisions between multiple tasks if they demand attention at exactly the same time. The memory-for-goals theory, also based on ACT-R (Altmann & Trafton, 2002), handles this by assuming each of the task goals of the system has a certain activation, and the choice between tasks is decided in favor of the goal with the highest activation. This works very well for situations with multiple goals, but it does not automatically generalize to situations in which distractions are not related to goals.

For distractions by external stimuli, the second type, relevant theories are those of specific interference or more general increases in noise in performance (e.g., VandeKerckhove & Tuerlinckx, 2007). When people are better able to select the relevant information from a display, they are less distracted (Posner & Petersen, 1990). The ability to resist this type of distraction is related to the ability to deal with response conflicts (Botvinick, Braver, Barch, Carter, & Cohen, 2001). Another factor that determines the intrusiveness of the distraction is its salience; the more salient the external stimulus, the more distracting it is. To overcome distraction by external stimuli, subjects need some form of control (Botvinick et al., 2001; Lavie & de Fockert, 2006). To summarize, the extent to which external stimuli can disrupt performance is determined by the strength of the goal, the ability of that goal to activate the right actions, and the strength or salience of the distractions.

For the third type of distraction, mind-wandering, several theories have been put forward (see Christoff, Irving, Fox, Spreng, & Andrews-Hanna, 2016; Smallwood, 2013; Smallwood & Schooler, 2015, for reviews). A possible explanation, the *current concerns hypothesis*, is that mind wandering is caused by goals and intentions that are currently not tied to perception and action (Klinger, Gregoire, & Barta, 1973). If this competes with goals that are tied to perception, the situation is similar to the multitasking situation in which multiple processes compete for shared resources.

McVay and Kane suggest that mind-wandering arises primarily as a failure of control, such that cognitive resources are directed away from the primary task into task-unrelated thinking. According to this theory, mind-wandering occurs when subjects do not have enough control resources to keep their minds focused on the task at hand (McVay & Kane, 2009, 2010). Alternatively, mind-wandering can arise when the cognitive system is understimulated and idling, in line with experiments showing more self-reported mind-wandering in a simple choice response task than in a similar task that involved working memory (Smallwood, Schooler et al., 2011). Yet other theories instead state that mind-wandering arises when a person is not aware where their attention is placed, and as such mind-wandering is associated with failures of *meta*-awareness (Schooler et al., 2011). The idea is that when a person exerts *meta*-cognitive control over where thoughts are going, then mind-wandering, which is a more spontaneous process, will not arise (Christoff et al., 2016). Evidence for this theory comes from studies in which subjects are not just asked whether they were on– or off-task at random moments in the task, but also how aware they were of where their attention was (Schooler & Schreiber, 2004). When people reported not being aware of where their attention was, they were more likely to be off-task.

3. A combined account of distraction

Many experiments and studies of distraction and mind wandering aim to distinguishing between different types of distraction and mind wandering, by separating external from internal distraction, and whether or not it is linked to intentions. Alternatively, it can be useful to look for unification: how can different modes of thought be explained by the same underlying cognitive mechanisms. Smallwood's *process-occurrence* framework (2013) is an example of this type of explanation. In this framework, internal and external domain-specific inputs compete for domain-general processing resources. The framework in able to encompass several of the explanations for mind wandering outlines in the previous section.

The account we present here takes this a step further by providing an implemented model that can predict experimental results. Translating a "verbal" theory into an implemented model requires concrete choices about the meaning of certain concepts, such as resources, that are otherwise left relatively underspecified. Contrary to most approaches the model does not distinguish between perceptual input and internal representation, but instead assumes both have a similar influence on the direction of thought processes.

As described in the previous section, important factors for distraction are the availability of resources, the exertion of control, and the presence of distracting stimuli in the environment or internally in the mind. First we need to know how people become distracted. Second, once people become distracted, the main task and the distraction coexist and compete for resources, and we need to be able to predict how they interact, and which one will prevail. Our starting point is the *threaded cognition* theory of multitasking (Salvucci & Taatgen, 2008). Threaded cognition can be considered to be a more precise version of the multiple resource theory by Wickens (2002, 2008) that is instantiated as a computer model. Threaded cognition assumes that people have several cognitive resources that can operate in parallel (following ACT-R: vision, audition, vocal, temporal, motor control, working memory, declarative memory, and procedural memory). At any moment in time, a particular resource can only be used for a *single* task. If multiple tasks need the same resource, it may mean that a task needs to wait, which, if the task is time-critical, may lead to errors. Resources differ in how easily they can be shared: a declarative memory retrieval may take less than a hundred milliseconds, which means that if multiple tasks need this resource delays will be relatively modest. In contrast, a task may need working memory for several seconds or even more. Therefore two tasks that both need working memory typically show strong interference effects (Borst, Taatgen, Stocco, & van Rijn, 2010; Borst, Taatgen, & van Rijn, 2010; Katidioti & Taatgen, 2014).

A logical extension of threaded cognition is that potential distractors can only be successful if they require a currently unused resource (assuming distractions are treated in the same way as tasks.) According to the theories of visual distraction and mind wandering discussed in the previous section, competition for resources is driven by the strength of the current task goals (potentially enhanced by explicit control processes), the strength and saliency of external stimuli, and the strength of association between distracting memory representations.

The approach we take is as follows. We assume that each task has a particular strategy in which it uses resources. The control process involves coordination between the resources in terms of activating new resources and transferring information. This process is carried out by mental operators similar to production rules in theories such as ACT-R (Anderson, 2007) and EPIC (Meyer & Kieras, 1997), and operators in Soar (Laird, Newell, &

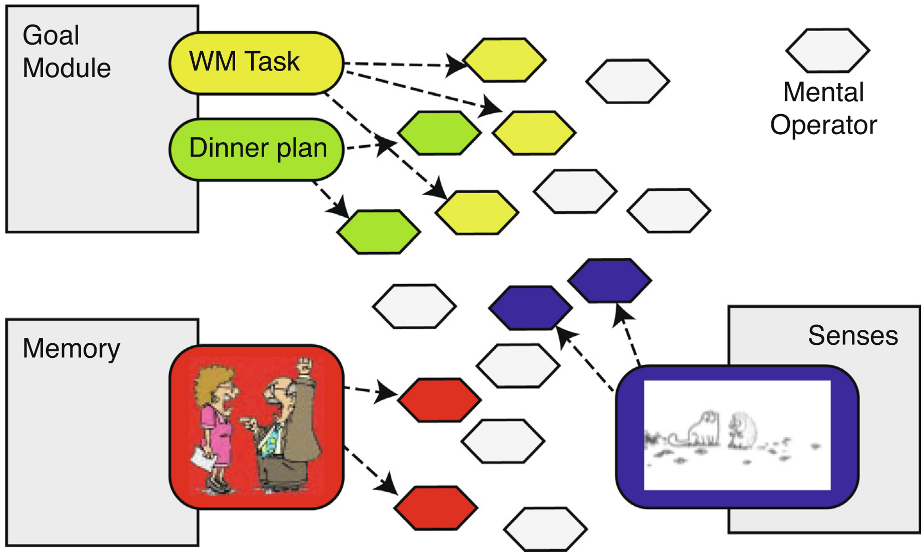

Fig. 1. Illustration of how multiple sources compete for mental operators, representing a situation in which someone is performing a working memory task while at the same time thinking about dinner plans. The working memory task has evoked a memory about a fight happening earlier in the day, while in the corner of the screen there is a distracting cat movie. Resources are depicted by gray squares, sources of spreading activation are depicted by rounded rectangles, and operators by hexagons.

Rosenbloom, 1987). The competition for resources therefore targets these mental operators.

Fig. 1 illustrates a general outline of the model. Operators are needed to control the flow of information between resources to carry out tasks (or distractions), and they compete among each other.

There can be multiple active tasks, represented in a goal module, that, depending on their importance, spread a certain amount of activation to mental operators associated with that task. At the same time, sensory input also spreads activation to operators that are related to processing that sensory information. Moreover, active memory traces can spread activation to operators that elaborate on that information. The figure shows this as a competition between four different tasks, but task representation, perception and memory can (and typically will) also support each other: a new stimulus for the working memory task together with the task goal can both activate an operator to remember that stimulus. Note that in this setup there is not "special" status of the current goal(s): an active goal makes it more likely that an operator relevant for that goal will be selected, but does not ensure it. In a sense, this architecture is agnostic on whether operators serve a goal, or a distraction.

In order to make specific predictions about distraction, the principles outlined above have been implemented in the PRIMs cognitive architecture (Taatgen, 2013). PRIMs is based on the ACT-R cognitive architecture (Anderson, 2007) and inherits many of its structures and mechanisms, in particular its modular structure, and the way in which memory activation is calculated and used. The following aspects of PRIMs are more or less identical to ACT-R: operators (productions in ACT-R) transport information between different cognitive modules, such as vision, audition, motor, long-term declarative memory, working memory (in ACT-R: the imaginal buffer), and currently active goals. To facilitate this transport, every module has a buffer. The content of the buffer is the product of the current activity of a module, for example the buffer of the vision module has the currently attended visual object, the buffer of declarative memory has the item that has last been retrieved from memory, and the buffer of working memory holds an item that is currently "in" working memory. Moreover, there is a goal buffer that can hold one or more task goals. Cognitive processing in PRIMs therefore takes place within modules (each of which has their own particular properties) and between modules, where operators match and coordinate the flow of information.

The main difference between PRIMs and ACT-R for the purpose of this article is that operators take the role of production rules. Operators in PRIMs are more limited in what they can do compared to other architectures: they are composed of primitive operations from a finite set, all of which are carried out in parallel. The details are outside of the scope of this article, and are not important for the models discussed (but for how they can be used to model transfer, see Taatgen, 2013). Selection of production rules in ACT-R is based on utility, which is a single value for each production. Utility works well as a conflict resolution mechanism within a task, but if we want to use productions/operators for different tasks it is too simple. PRIMs operators are used for many different tasks, which means their utilities may differ based on the context. The activation concept, which we will detail in the next paragraphs, combines past use and the current context, and is therefore better suited for the selection process in a multitask context. The difference in operator selection also discriminates the PRIMs approach from the memory-for-goals approach

(Altmann & Trafton, 2002). Whereas the competition between tasks in that theory plays out at the level of the task goals, in PRIMs it plays out at the level of individual operators. It is therefore possible to model distractions that are not based on goals. More details on PRIMs, and various comparisons to ACT-R, can be found in the PRIMs tutorial document and examples, which can be found on https://github.com/ntaatgen/PRIMs-Tutorial.

A formal description of operator selection is as follows: Operators are considered to be elements in declarative memory, and have an activation value just like any other element in declarative memory (see for details on how activation is calculated Anderson, 2007). Activation determines the order in which operators are tried: the operator with the highest activation of which the conditions are satisfied is selected. Activation for operator i is calculated using the following equation:

$$A_i = B_i + \sum_k^{buffer} \sum_j^{slots} S_{ji} W_k + noise$$

In this equation, B_i is the base-level activation that reflects how often an operator has been used in the past. In the models discussed in this article we will not vary base-level activation, so in every model it has a constant value that is the same for all operators. The double summation on the left of the equation calculates how much activation the operator receives from the current contents of the buffers. Each buffer has a number of slots, and the content of each of these slots spreads activation. The W_k parameter determines how much activation a particular source k spreads, and the Sji parameter determines how strongly chunk j in the buffer and chunk i in declarative memory are associated. For example, if the buffer for working memory has the *addition*, *two* and *three* values in its slots, any operator that is associated with any of these values receives extra activation. Possibly an operator *retrieve* that initiates a memory retrieval may be associated with *addition*, which means that Saddition,retrieve > 0. If we assume Wworking-memory is also positive, then the *retrieve* operator receives extra activation and is therefore more likely to be selected.

Although there are all kinds of reasons why operators are associated with goals, facts and memory, and each other, two types of associations are always set by default:

Operators are typically strongly associated with one or more tasks, which means that we typically prefer operators that achieve our current task.

Operators that are associated with a particular task are also associated with each other. This means that the system prefers to select an operator for the same goal as the previous operator.

A final component of activation is (logistically-distributed) noise. As a consequence, operator selection is always probabilistic: all components increase or decrease the likelihood that an operator is selected, but a single component never guarantees it.

3.1. Parameter fitting

When building a model of distraction, the modeler has to decide what knowledge is needed to perform a particular task by specifying the appropriate operators, and what operators are needed to model distractions. Operators have a limited power, in that they can only transport information between resources. Therefore the way a task is implemented is reasonably constrained.

Additionally, the modeler has to decide the relative priorities of the tasks by setting strengths of association between context elements and operators (i.e., the dashed arrows in Fig. 1) by specifying S_{ji} parameters. The S_{ji} parameters between the tasks and the operators have default values, but for items in other buffers (vision, working memory, declarative memory) it is up to the modeler to decide.

What this means is that the modeler sets up the knowledge for the individual tasks and distractions, but does not specify how they interleave. The simulation of the model then provides a prediction of how the different operators interleave in a particular task context, and how this plays out in terms of choice, latency and accuracy. Changes in the associative strength parameters may influence to what extent tasks or distractions are performed in the simulation, but do not control it completely: the simulation tries to fill all empty time with processing, which may mean that sometimes a low-priority task will be performed no matter what.

3.2. Summary

The proposed model is a combination of elements from many existing models, including ACT-R and EPIC (Anderson, 2007; Meyer & Kieras, 1997), threaded cognition (Salvucci & Taatgen, 2008), theories of visual distraction (Lavie, 2005), models related to control (Botvinick et al., 2001, McVay & Kane, 2010) and models related to the use of resources (Hockey, 1987, Katidioti & Taatgen, 2014; Smallwood & Schooler, 2015).

The key points are:

- Cognitive resources can only be used for a single purpose at a time. Multiple tasks, including mind wandering and distraction, can be done in parallel as long as their use of resources does not overlap in time.
- Distraction and mind wandering can be triggered by external and internal sources (vision, memory retrieval, unresolved goals, etc.).
- A distraction can only be successful if it initially targets an unused resource.
- If both the main task and the distraction compete for the same resource at the same moment in time (assuming neither used it directly before that moment), the most active operator associated with that task or distraction determines the outcome.

- It is implemented in a computational modeling system that can make concrete, quantitative behavioral predictions.

We will support the theory by modeling three different experimental paradigms. In the first paradigm, performance demands are low, but in one condition the working memory resource is not occupied, while in the other condition it is. In the second paradigm, performance demands are high, so there is a strong competition for resources. In the experimental condition, stimuli in the task prompt mind wandering, decreasing overall performance on the main task compared to a control condition. In the third paradigm task demands are varied, and the distraction is visual. In all three cases, distraction can be explained by operators that target unused resources.

4. Phenomenon I: Mind wandering

The first example we will discuss is a model of a mind wandering experiment by Smallwood et al. (2011). Typically, mind-wandering experiments have low cognitive demands, making it likely that mind-wandering occurs. Subjects performed either a Choice Reaction Task (CRT) or a Working Memory (WM) task. In both tasks, they saw a sequence of 2–5 black digits with a presentation time of 1000 ms, interleaved with fixation crosses that stayed on screen between 900 and 2100 ms (see Fig. 2). After the sequence of digits in the CRT task, they were presented with another (colored) digit, to which they had to respond odd or even. In the WM task they saw a colored question mark, to which they had to respond odd or even on the basis of the last digit they saw (3 in the example in the figure). Occasionally, subjects received a thought probe at the moment they had to respond: instead of the usual response they had to say whether or not they were attending to the task. The main finding was that, as predicted, mind-wandering (as measured by the responses to thought probes) occurred more frequently in the CRT task (49%) relative to the WM task (32%).

Our model of this task makes a number of assumptions about mind-wandering. The first assumption is that mind wandering is initiated by a retrieval from memory, possibly an episodic memory, or any other currently salient memory trace (this assumption is supported by neuroimaging data from Christoff et al., 2016, in which mind wandering typically initiates in the default network that includes the hippocampus, and later proceeds by recruitment of the fronto-parietal control network). This retrieval can be initiated by an operator that is activated because there is nothing else to do at that moment, or because it receives activation due to some event in the context. In this first model of distraction we will stick to the first possibility: because there is nothing to do (in agreement with Smallwood et al., 2011′s theory). After the memory retrieval, there is a possibility that the retrieval will lead to additional elaboration in which the retrieved thought or episode is placed in working memory. The assumption is that elaboration is only possible if working memory is not used by the main task at that moment. This assumption is a key part of the threaded cognition theory, and has been tested in several experiments (e.g., Borst et al., 2010, in which two separate tasks only showed strong interference if both had a working memory component). If the first elaboration succeeds, the mind-wandering process has gained a foothold in working memory, making further elaboration steps increasingly likely.

The model assumes that the task itself is implemented by a set of operators that attend the digits, and make the

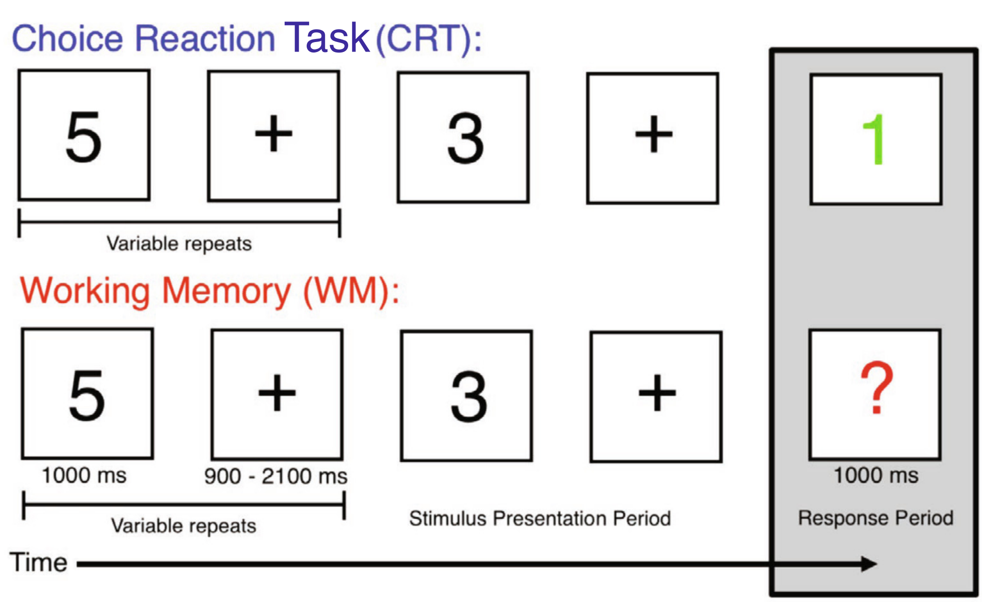

Fig. 2. Design of the Smallwood et al. (2011) experiment. Reprinted with permission from Smallwood et al. (2011). Copyright 2011 Smallwood et al.

appropriate responses at the right moments. For the CRT model this means that it has to attend and then ignore black digits until a colored digit requires a response. The WM model has to take one additional step: it needs to store black digits in working memory (overwriting the previous one), and when the question mark comes up it carries out the same operators as the CRT model, but now on the basis of the digit in working memory.

Given the slow pace of the experiment, the task model has nothing to do for a large proportion of the time. In order to stay focused on the task, it has a *focus* operator. However, this *focus* operator is not as strong as the operators that actually process information, because it only receives spreading activation from the goal and not from any of the other buffers (in contrast to e.g., the attend operator, which is also activated by the visual input). Moreover, because it has to be carried our repeatedly, its negative self-association further decreases its activation. The focus operator can therefore lose the competition with a non-task related operator (the *wander* operator) that retrieves an (arbitrary) episodic memory. If this happens there are two possible continuations; either the retrieved episode is ignored and task-related processing resumes, or another operator (the *elaborate* operator) is activated, which stores the episode in working memory for further elaboration. Once an episode resides in working memory, the distraction (or mind-wander) has gained a foothold that allows it to reactivate the *wander* operator to do further retrievals and elaborations. In the model this is represented by a sequence of associated episodic memories that the *wander* operator will try to recall. However, this can only happen in the CRT model, because in the WM model, working memory is occupied by the most recent digit. In other words, the *elaborate* operator is not allowed to be activated, because the working memory resource it needs is occupied. As a consequence, mind-wandering remains shallow and intermittent in the WM model, but can become more prevalent and dominant in the CRT model, in agreement with findings by Smallwood, Nind, and O'Connor (2009).

Note that the we consider the *wander* operator as a good approximation of how distraction is initiated, targeting a single unused resource, and the *elaborate* operator as an approximation of all the possible thought processes that then recruit more resources, which can be extremely varied, and which we cannot possibly all capture in a model.

Fig. 3 illustrates the process. The left panel illustrates mind wandering in the CRT task. After attending the number "5″, the model tries to focus until the next number shows up. However, after a while the *focus* operator loses the competition from the *wander* operator. The *wander* operator retrieves an episodic memory related to breakfast. The *elaborate* operator decides to put that topic in working memory and to do further retrievals. However, at that time a new digit is displayed, which causes the *attend* operator to be reactivated. After deciding that nothing needs to be done with that number, the model again tries to focus. However, the breakfast topic is still in working memory making it even more likely for the *wander* operator to take preference over the *focus* operator, which in the example leads to a further train of thought. Fig. 4 shows the competition between the task and wander operators, taken from an arbitrary model trace, but matching Fig. 3.

The right panel of Fig. 3 shows the case of the working memory task. With the exception of the first few seconds of a trial, working memory is occupied with the last digit that was attended. The *wander* operator can still initiate mind wandering, but *elaborate* operators are blocked because working memory is occupied. Therefore the total proportion of the time the model wanders is much smaller.

If we run the model, we can check whether it was mind wandering or focusing before the final response. Fig. 5 shows the results, along with the data from Smallwood et al. (2011). The data from Smallwood were what subjects reported on a thought probe, whereas in the model this is based on direct inspection of what the model is doing.

The model from this experiment, as well as all other models discussed in this article, can be downloaded from https://github.com/ntaatgen/Distraction.

In addition to the smaller proportion of distraction in the WM task that Smallwood at al. found, they also observed that subjects in the CRT task were more likely to think about future events. Although the model does not represent the exact content of the mind wandering process, Smallwood's result is consistent with the model. The initial wander step can only retrieve memories, which are necessarily past episodes. Elaboration steps, on the other hand, can involve future planning (even though they do not in the model). In the WM condition, the model will never do elaboration steps, whereas in the CRT condition it does.

The parameters in the model mainly influence the competition between task (i.e., the focus operator) and distraction (i.e., the wander operator), and changing them can shift the activation curves in Fig. 4 up or down, and therefore the general proportion of distractions.

5. Phenomenon II: Mental distraction prompted by the task

In the model of the Smallwood et al. task, mind-wandering happens because the model has very little to do. This is an important reason for distraction, but not the only one, as discussed above. However, if we have a task that continuously keeps the subject engaged, distraction needs a stronger cue, because there is no "empty time" to fill.

5.1. Experiment 1a

We modified a complex working memory (CWM) task originally proposed by Redick et al. (2012). In the CWM task, subjects have to remember and recall a list of 3–5 letters. Between the presentation of each of the letters,

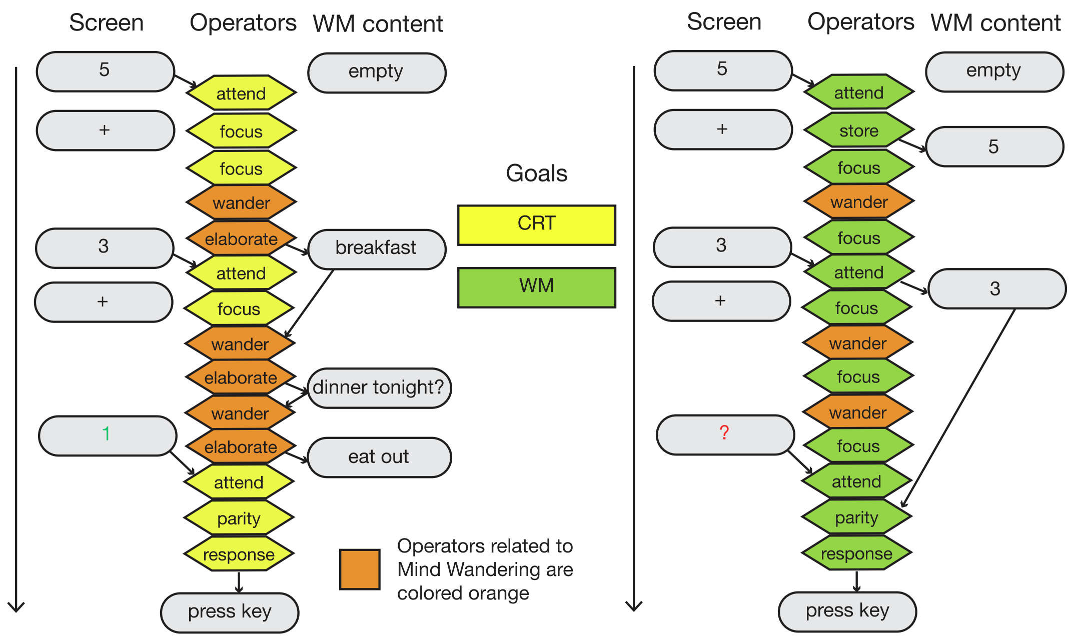

Fig. 3. Outline of an example of a model run of the CRT task (left) and the WM task (right). Time progresses from top to bottom. The leftmost column shows what is on the screen. The middle column shows the operators that are selected, with the color indicating the goal they are associated with. The rightmost column shows the content of working memory.

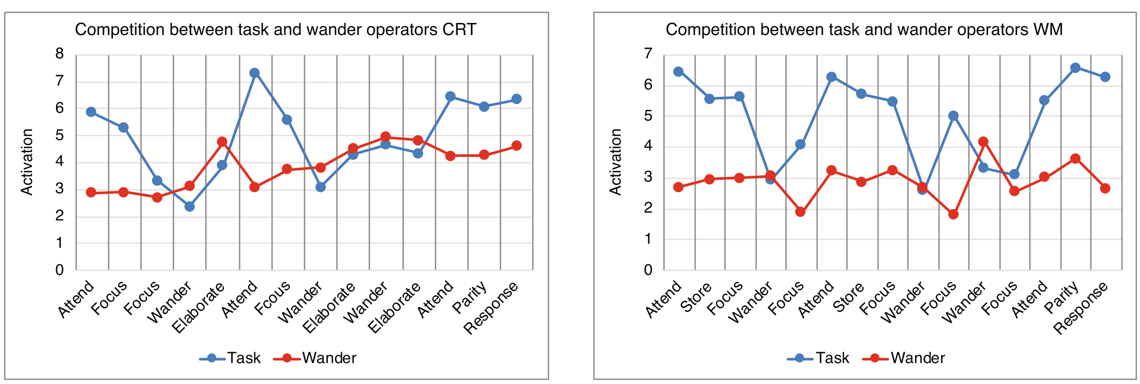

Fig. 4. Example of activations of the task- versus the distraction-related operators. Every time the red line is above the blue line, the model is distracted. On the x-axis the winning operators are displayed (from Fig. 3). In the CRT task, the wander operators gain activation after the first elaborate, because they are co-activated from working memory. In the WM task there is no opportunity for elaboration, and therefore the activation of the wander operators does not change. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

subjects engage in a choice task for 4 s. Subjects have to respond to presented words in accordance with the instructions for one of two task conditions, designed to manipulate the amount of mind-wander triggers. The processing words were drawn from a pool of a personality item questionnaire, such as happy, depressed, popular, daydreamer, etc. In the self-referential processing (SRP) condition, subjects had to respond by indicating whether the word was applicable to them, with the idea that this triggers self-related mind-wandering, which may also evoke concerns (D'Argembeau et al., 2007). In the control condition, subjects saw words that referred to objects, of which they had to decide whether they would fit in a shoebox.

The assumption of this design is that the processing task blocks any rehearsal processes, but that during the one-second blank and subsequent one-second presentation of the letter, rehearsal is possible, assuming the subject chooses to do so. Our expectation for this experiment was that responding to the personality question could prompt mental elaboration even beyond the response (Sui & Humphreys, 2015), in line with the idea that cues which trigger a person to think about themselves and especially their perceived deficits trigger highly automatic elaboration processes (e.g., Barnhofer, Crane, Spinhoven, & Williams, 2007; Wessel et al., 2014). This elaboration competes with rehearsal, and thereby disrupts recall performance.

5.2. Method

Subjects Subjects were recruited from the University of Groningen community, for a reward of 10 euros. Thirty

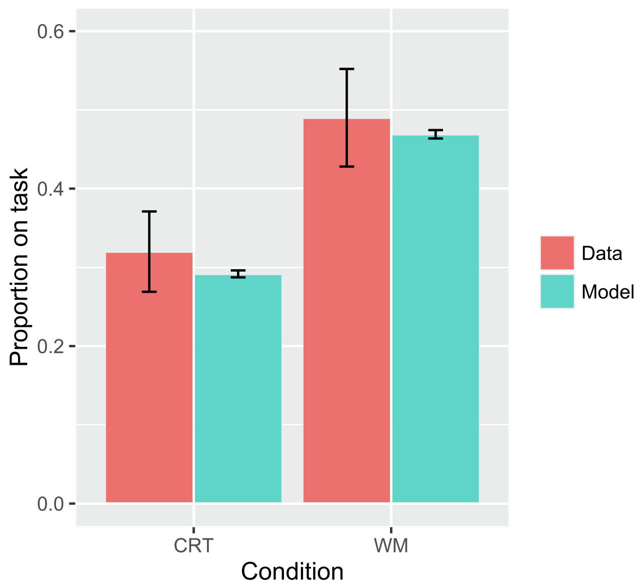

Fig. 5. Results of the Smallwood et al. experiment compared to the model results. Bars represent one standard error.

native Dutch subjects (18 female, age 22.4 ± 4.0) were included. Informed consent was obtained from all subjects.

Materials To-be-remembered stimuli were randomly drawn from the set of all consonants (i.e., B, C, D, F, G, H, J, K, L, M, N, P, Q, R, S, T, V, W, X, and Z). Within one trial no letters were repeated. The word stimuli were derived from the 50-item International Personality Item Pool questionnaire (IPIP) used for measuring the Big-Five factor markers as reported by Goldberg (1992). Examples of items are: Happy, Optimistic, Aggressive, Neurotic, and Kind. These words were translated into Dutch. For the control ("shoebox") condition, we used translated nouns from the Toronto Word Pool (Friendly, Franklin, Hoffman, & Rubin, 1982). Fifty words were selected to which the answer was an unambiguous yes, and another 50 to which the answer was an unambiguous no.

Procedure In this experiment subjects were required to remember presented letters while processing presented words (Fig. 6). For the this part of the task, subjects needed to remember letters that were presented one at a time on the screen for 1 s, and between each presentation there was 4 s of processing of word stimuli (self-referential or control). Before each letter presentation the screen was blank for 1 s. We included this delay on purpose to maximize the potential for distraction by self-referential processing triggered by the personality words earlier.

All stimuli were presented on a dark grey background with white text (Gill Sans MT, font height ~ 1 cm). Each trial started with showing the subject the current condition. For the self-referential processing condition this was "Does this word describe you? (Yes/No)", for the control condition this was "Does the object fit into a shoebox? (Yes/No)". All language in the experiment was Dutch; here we use the English translations for clarity. Subjects were asked to respond by pressing the left (labeled 'NO') or right 'ctrl' (labeled 'YES') buttons.

After the condition was shown, the following sequence was repeated with iterations equal to the span: a one-second blank screen, a random letter stimulus presented in the center of the screen for 1.0 s, and 4 s of the processing task (SRT or control). Within the processing task, as soon as a subject responded to a word the next word would be presented. Therefore several words were processed between two memory items. If there were less than 700 ms remaining, the screen would stay blank for the remaining time to prevent subjects being flashed by a stimulus after responding to the last word.

The recall phase was indicated by a number of underscores equal to the current span (the spans used were 3, 4 and 5, as is common in CWM span tasks, Conway et al., 2005). The underscores were replaced by the user's input as they started typing. Error correction was possible by using the backspace key. Subjects were instructed to guess if they couldn't remember a letter. When they entered the last letter the feedback was presented in the form of "[x] out of [span] letters correct". They also received their average response time in the processing task as well as their percentage of correctly judged processing items for the control condition. Due to the subjectivity of the self-referential processing condition there was no score shown. A pilot study showed that subjects were consistent with their previous responses in the self-referential processing condition, indicating that feedback on this was not critical.

The experiment consisted of 12 blocks, with one block containing each combination of span and condition once,

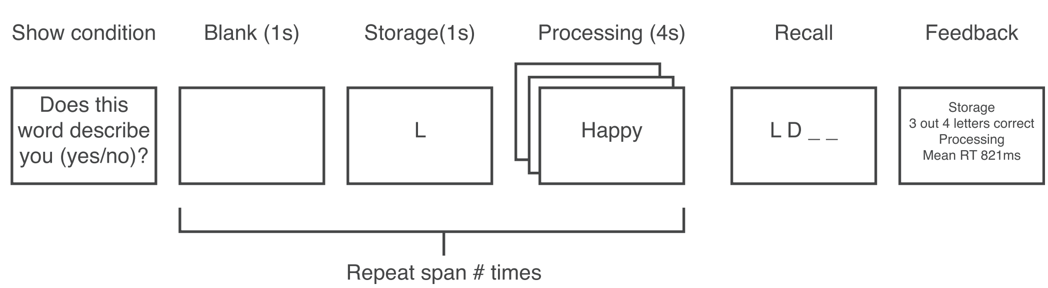

Fig. 6. Outline of the procedure of experiment 1a and 1b. In the processing stage words are presented that subjects need to respond to until 4 s have passed.

so for a total of 72 trials. The total duration of the experiment was approximately one hour. The experiment was programmed in PsychoPy (Peirce, 2007).

Scoring The recall success was scored using partial-credit unit scoring (Conway et al., 2005). That is, the score for each trial was calculated as number of items in correct serial position divided by the span of that trial.

5.3. Model

The model has two active tasks: the memory task that reads and consolidates letters, and that tries to rehearse them when there is an opportunity, and the processing task that generates responses for either the shoebox or the SRP stimuli.

The memory task has operators for a number of different situations. It has two operators to store presented letters. The first operator is activated when a letter is displayed, and places this letter in working memory together with the position of the letter in the list (first, second, etc.) The second operator then consolidates the letter in declarative memory. The memory task attempts rehearsal when there is nothing on the screen, or when whatever is on the screen has been processed. It will start rehearsing the first item in the list, and proceeds towards the end. Finally, there are operators to recall the list in the recall stage of the trial.

The processing task has three operators. A first operator reads a word, and retrieves the semantic content of that word from declarative memory. Once the word has been retrieved, a second operator retrieves whether the trait is applicable to the person, or—depending on the condition—whether the object fits in a shoebox. The assumption of the model is therefore that the decision can be made by a retrieval from declarative memory. A third operator presses the appropriate response key.

To model distractions we use the same operators as in the earlier mind-wandering example. This means that the *wander* operator can intervene at any moment to retrieve an episodic memory. However, under normal circumstances this will not happen as often as in the mind-wandering experiment, because the task normally keeps the model fully engaged. However, a strong association between the meaning of a word and the *wander* operator may start a distraction.

We assume that associations between the meaning of SRP words and the *wander* operator have been learned in the past, because these words are more frequently combined with mental elaboration processes than the item words used in the shoebox condition.

Fig. 7 illustrates how the model performs the task. When a personality word is displayed on the screen, a task-related operator retrieves the meaning of the word. Normally, this is followed by an operator that retrieves a related memory trace to determine the answer. However, it is also possible that the *wander* operator is activated, which is more likely if there is an association between the word meaning and the *wander* operator. We assume this is the case for the SRP words, but not (or to a lesser extent) for the shoebox item words, in agreement with studies showing that self-related cues evoke elaboration processes (Wessel et al., 2014). In the example, the word "Popular" is read and responded to normally, but the word "Angry" prompts a thought about a roommate being angry about the breakfast dishes. This retrieval may still be followed by regular task-related operators, but it may also trigger an elaboration operator that uses working memory to formulate the plan to clean the dishes tonight. Eventually, task operators take over again and produce the response.

After four seconds the processing task ends, and is followed by a one-second blank that precedes the next letter. During that time, the model can either perform rehearsal, primed by the activate rehearsal goal, or further elaborate on a thought that is still in working memory (if there is one). Because the SRP words spread more activation to the mind-wandering operators than the shoebox objects, mind-wandering will win the competition more often from rehearsal in the self-referential processing relative to the shoebox condition, thereby decreasing memory performance.

5.4. Results of the experiments and model

In this section we present the main results, additional results can be found in the Appendix. If subjects did not score above 85% correct on the control task, we assumed they did not perform the processing task as intended. This led to the exclusion two subjects.

Fig. 8 shows the accuracy results, including the model fit. Accuracy is expressed as partial-credit score, which is the proportion of correctly reported digits. Subjects performed much worse in the SRP condition than in the control condition, clearly indicating that the processing task had a larger disruptive effect on the memory task in that condition.

Given that response times on the processing task were different for the control and SRP conditions (see Appendix for details) with larger variations in the latter, we are including the mean response time per subject on the SRP processing items as a variable in the analysis.

To this end we fitted logistic mixed effect models to predict the partial-credit score with condition, mean SRP processing time, and span as fixed effects, and subject as random effect, resulting in the models shown in Table 1. The analysis confirms a clear effect of condition on accuracy. Mixed effect models that also included interactions did not provide better fits of the data. In addition to the effect of condition, subjects who took more time to respond to the SRP processing items also suffered from a decreased score on partial-credit score on the memory task. It is clear that this additional time is not used for rehearsal, because otherwise an increase in performance would have been expected. Also, controlling for this aspect still leaves the significant impact of condition intact.

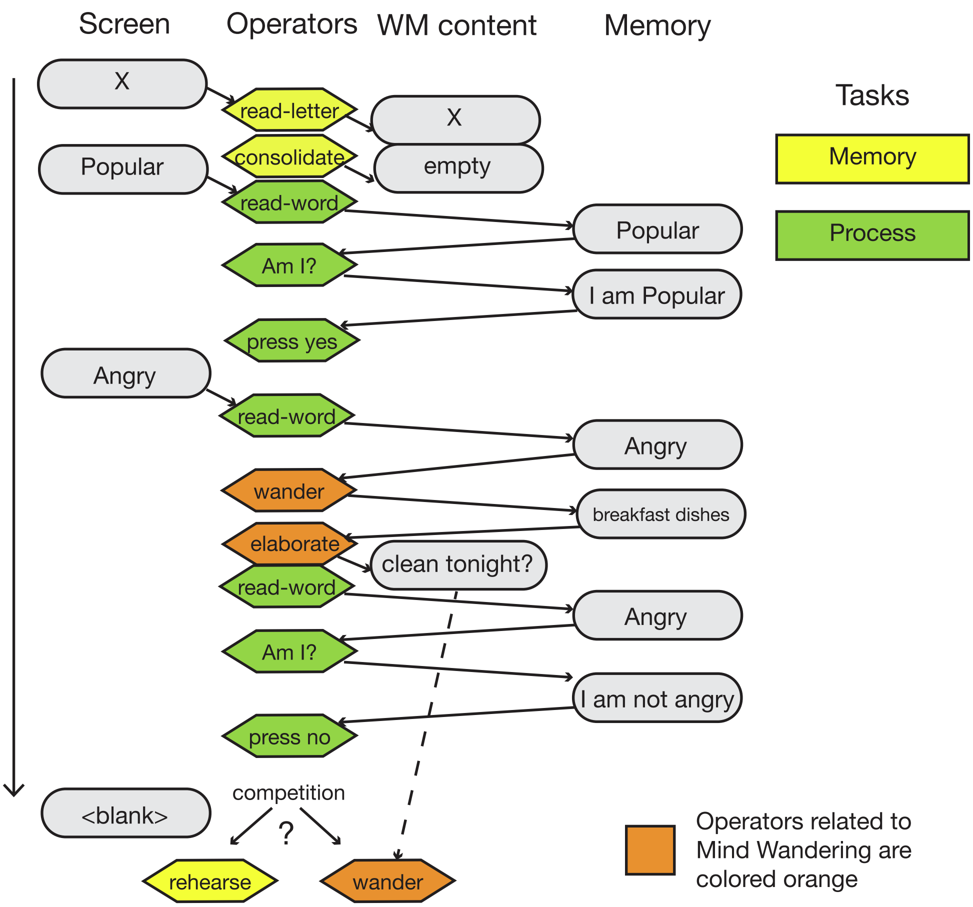

Fig. 7. Outline of the model for the complex WM task. Conventions are the same as in Fig. 3, but here there is an additional episodic memory column ("Memory").

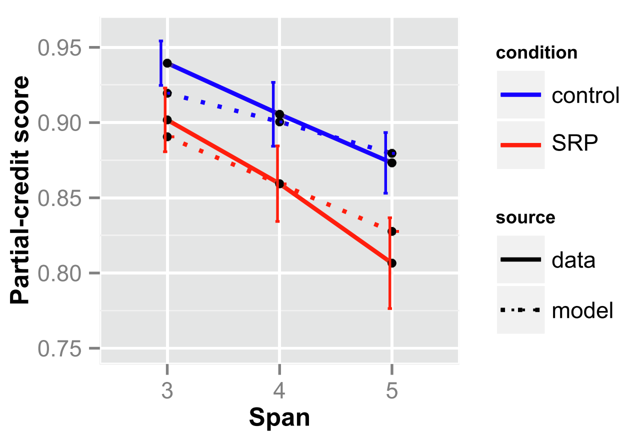

Fig. 8. Results of Experiment 1a with the model (dashed lines). Error bars in this, and all future figures, are standard errors.

Table 1
Mixed-effects model analysis of the partial-credit score for Experiment 1a.

Factor	Estimate	SE	z-value	p-value
Intercept	6.860	1.123	6.08	
Condition SRP	−0.861	0.169	−5.10	<0.001
Mean SRP processing RT	−2.441	1.001	−2.44	0.015
Span	−0.305	0.100	−3.04	0.002

According to the model, a part of the process of distraction happens during the processing task: a new item may lead to distracting memory retrievals, which subsequently leads to a choice to wander instead of rehearse (Fig. 7). The finding that the mean SRP processing reaction time is a factor in the score is therefore consistent with the model. We can test this more directly by testing whether the response times on the processing task within a trial predict the partial-credit score for that trial. To prevent this test from being dominated by the overall effect of condition, we do this separately for the control condition and the SRP condition. This analysis shows in both conditions of both Experiment 1a and 1b, that the response time during processing does indeed predict the score. The exact results can be found in the Appendix.

The relation between processing time and the partial credit score, averaged over both conditions, is also shown in Fig. 9, which shows both the experimental data and the model. To obtain variation in the model, the association between SRP words and the wander operator was determined randomly for each run, reflecting the fact that not every individual is equally likely to be distracted by SRP words. Other possible parameters that influence working-memory capacity have been kept constant, which

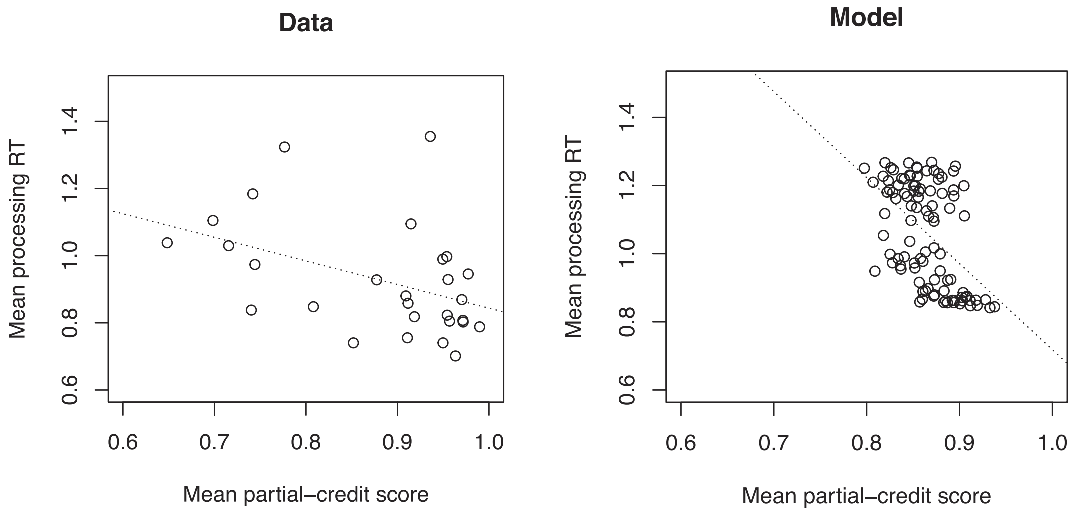

Fig. 9. Relation between the average RT on the processing task, and the mean partial-credit score. Each point in the left panel is one subject, and each point in the right panel is one run of the simulation.

explains the more limited range of partial-credit score for the model.

The results of the model depend on a number of parameters. A first main parameter is the retrieval threshold that determines below which activation level items are forgotten. Changing the parameter affects the global probability of recall. The second parameter is the association between SRP words and the wander operator. Although we varied this parameter to obtain the results in Fig. 9, the mean value of the parameter affects the difference between the control and SRP conditions.

5.5. Discussion

The results clearly show that self-referential processing has a strong effect on the capacity to maintain a list of items in memory. According to the model the memory impairment arises from a lack of rehearsal. Moreover, the model predicts that poor performance on the memory task is preceded by a slowdown in the processing task, which is also confirmed by the experiment.

The model provides two (related) predictions that were not tested in the current experiment. The first is that the model can tell us whether it was on-task, or whether it was distracted at the moment before it had to type in the answer. To determine this, we looked at the last action the model took before typing the answer. If this was a subvocalize action, we count that as on-task, while a wander or elaborate action is counted as off-task. If the model was in the control condition, it is on-task 72% of the time. However, if the model was in the SRP condition, it was on-task only 27% of the time. Furthermore, we can determine the correctness of the model depending on whether the model was on-task or distracted. If the model was on-task, it was correct 91% of the time, whereas this dropped to 86% when it was distracted. To test these predictions, and to replicate the previous experiment, we repeated the experiment, but now inserted so-called thought probes in half of the trials.

5.6. Experiment 1b

Experiment 1b is identical to Experiment 1a, except that in 50% of the trials (randomly determined, but balanced by span and condition), subjects were given a thought probe after they had entered the letters and before they received feedback. In this thought probe, they were asked about the moment after the last processing item and before typing in the recalled items. For this, they had to choose between: “I tried to remember the letters” (on-task), “I was still thinking about the words in the processing task” (processing-words), “I was evaluating aspects of the task (such as: my performance, difficulty, duration)” (task-related interferences), “I was distracted by my environment (noise/temperature, etc.), or my physical state (hunger/thirst, etc.)” (external distraction), “I was daydreaming/I was thinking about task unrelated things” (mind-

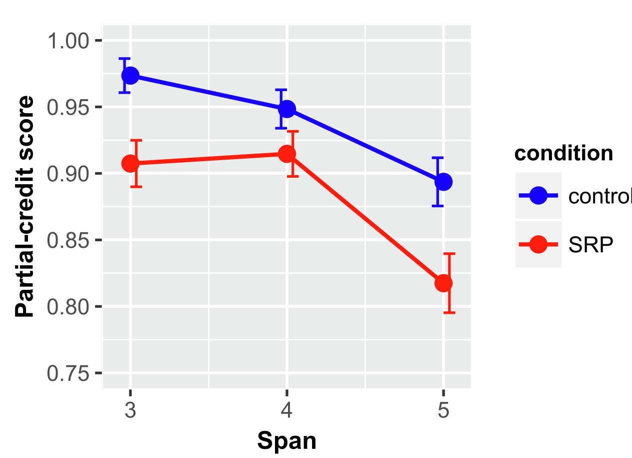

Fig. 10. Accuracy results of Experiment 1b.

wandering), "I wasn't paying attention, but also wasn't thinking about anything specific" (inalertness). This resulted in 18 thought probes per condition per subject.

Subjects 21 native Dutch subjects (19 female, age 20.7 ± 2.4) were included, all different from the subjects of Experiment 1a. Written informed consent was obtained from all subjects.

Results Fig. 10 shows the accuracy results of the experiment, which are, although overall somewhat higher, consistent with experiment 1a. The top rows in Table 2 show the mixed effect model of the partial-credit scores, which again has main effects for span and condition. Like in experiment 1a, subject was entered as a random effect, and there was no interaction. Contrary to the previous experiments, average processing time per subject on the SRP did not have an impact on accuracy. However, the more fine-grained analysis of the impact of processing time on accuracy yields results similar to the earlier experiments (see Appendix).

To see whether subjects were indeed more distracted in the SRP condition we plotted the responses to the thought probe question by condition in Fig. 11. Indeed, we see that the proportion on-task is smaller in the SRP condition, and that instead subjects are thinking about the processing task more often, even though it no longer serves any task requirement. The other response categories are not affected by condition. The middle part of Table 2 contrasts reports to be on-task with the other responses, with a generalized mixed-effects model of on/off-task report with condition as fixed effect, showing that in the SRP condition subjects are significantly less on-task than in the control condition. The control condition data are consistent with the model (71.7% in the data vs. the 72% prediction), but subjects in the SRP condition are far more often on task than the model predicted (61.6% data vs. 27% prediction). A possible explanation for this discrepancy is that the model assumes no associations with mind-wandering for shoebox items, and a strong association for each of the SRP words. For real subjects these associations are probably less consistent (i.e., they may not have strong associations with each of the SRP words, while some shoe-box items may have associations). Moreover, the model spends all of its time in the control condition rehearsing, while subjects may have a more satisficing approach to the task.

Do subjects perform better when they reported that they were on-task? Fig. 12 shows the partial scores plotted by thought-probe response. Performance was better when subjects were on task, which was also confirmed by fitting a generalized mixed-effect model on the partial-credit scores with on-task as fixed effect (bottom part of Table 2). The model predicted a 91% score for on task reports, and 86% score for off task reports. The gap in the real data is somewhat larger, which means that the model has overestimated the ability of SRP words to produce distraction, but underestimated how much this affected memory retention.

So, can we consider this a success or a failure of the model? The quantitative fit is correct, and the qualitative fit is quite good for three of the values, and off for the fourth. Refitting the model with slightly different parameters would enable it to capture the results more precisely: the associations between the processing words would need to be made a bit more random, decreasing mind-wandering in the SRP condition. This would also decrease the gap between the accuracies of on– and off-task.

6. Phenomenon III: Visual distraction

One of the challenges of studying mind-wandering and distraction is that it is hard to measure distraction directly. In the previous experiments we concluded that a decrease in performance must have been due to distraction. The evidence was based on self-reports, which concurred with this conclusion. Our general model of distraction claims to be relevant for all types of distraction, including visual distraction. The advantage of visual distraction is that it can be measured directly using eye tracking. The goal of the next experiment is to find evidence for visual distraction, and test predictions that the general resource-availability theory makes.

The general setup is as follows: subjects in the experiment are given a main task. On the side of the screen, a movie is played. The movie is unrelated to the task, and subjects receive no instructions about it. The number of times that subjects look to the movie while performing the task is an index of how distractible they are.

The main task consists of the game of Memory (sometimes called Concentration), in which they have to turn over cards (and memorize them) to find pairs that match. In the variation we used in the experiment there are equa-

Table 2
Mixed-effects model analyses of Experiment 1b.

Dependent Variable	Factor	Estimate	SE	z-value	p-value
Score by condition and span	Intercept	5.482	0.637	8.60	
	Condition SRP	−0.677	0.218	−3.10	0.002
	Processing time	−0.559	1.376	−0.40	0.68
	Span	−0.544	0.136	−4.01	<0.001
On Task by condition	Intercept	1.154	0.267	4.32	
	Condition SRP	−0.55	0.17	−3.21	0.0014
Score by On Task	Intercept	1.974	0.263	7.51	
	On Task	1.554	0.335	4.64	<0.001

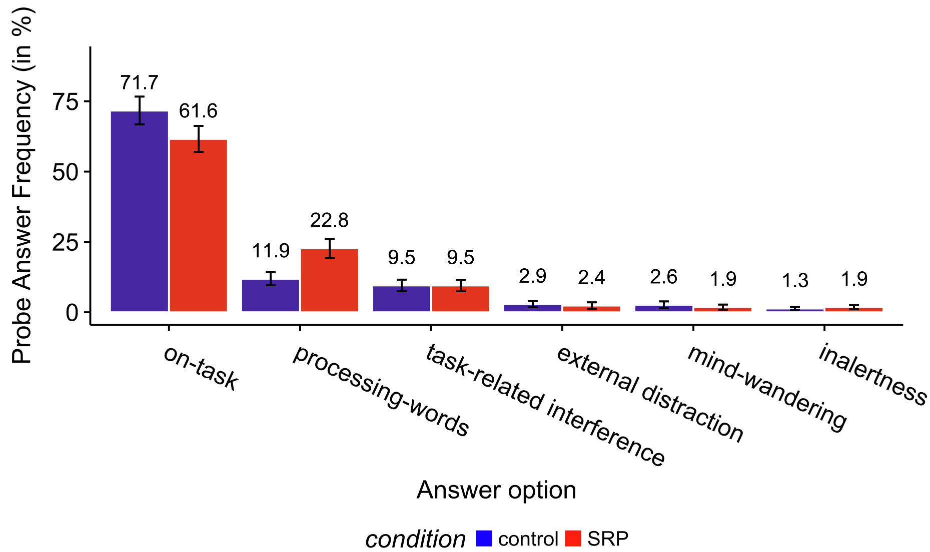

Fig. 11. Proportion of responses on the different categories in the thought probe split by condition.

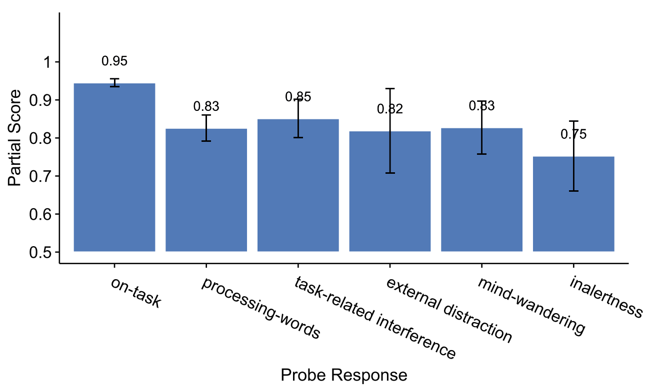

Fig. 12. Partial score on the memory task given the response on the thought probe.

tions on the cards that subjects need to solve instead of pictures. The goal is to find pairs of cards in which the solution is the same. In this task, the difficulty is manipulated by the difficulty the equations. At first glance, the obvious prediction would be that there will be more distraction in the easy condition, because the task is less demanding. However, the resource-availability theory predicts the opposite: distraction increases with difficulty, because during the solving of a difficult equation, the visual resource is not used and therefore can be co-opted by distraction processes.

6.1. Experiment 2

6.1.1. Method

Subjects Twenty-three subjects (14 female) participated in the experiment. One male subject was removed because of malfunction of the eye tracker. The remaining 22 subjects had a mean age of 23.8. All subjects had normal or corrected-to-normal vision, gave informed consent for their participation and received monetary compensation of 10 Euros.

Task The main task of this experiment (also used in Anderson, Fincham, Schneider, & Yang, 2012; Katidioti, Borst, & Taatgen, 2014) was a variation of the game known as Concentration or Memory, replacing images with equations (Fig. 13). Subjects had to click on a card with the left mouse button, mentally solve the equation that appeared on the card, remember the value of X and continue by clicking on another card. In this version of the game, cards are opened one at a time instead of in pairs and a match is made when the opened card matches the previously opened card (the word “MATCHED” appeared on the back of these cards and they could not be clicked again). In our instantiation there are 16 cards (8 pairs) with equations on them, arranged in a 4 by 4 matrix (Fig. 13). In the equations, X was the unknown value and was always an integer from 2 to 9. There were three difficulty levels, each of which was presented in a 15-minutes block:

Easy: $a + b = X$, where a and b were integers between 0 and 9
Medium: $X + a = b$, where a was an integer between 1 and 9.
Hard: $a * X + b = c$, where a and b were integers between 1 and 9.

Two cards are said to match when they have the same value for X. For example the cards “$2 * X + 2 = 12$” and “$3 * X + 4 = 19$” are a match, since $X = 5$ in both of them.

In addition to the experimental window with the memory game, there was also a video playing constantly on the screen (Fig. 13). This mute video was compiled of 37 clips of “Simon’s Cat”, with a total duration of 50 min. The video was a black and white cartoon with simple line

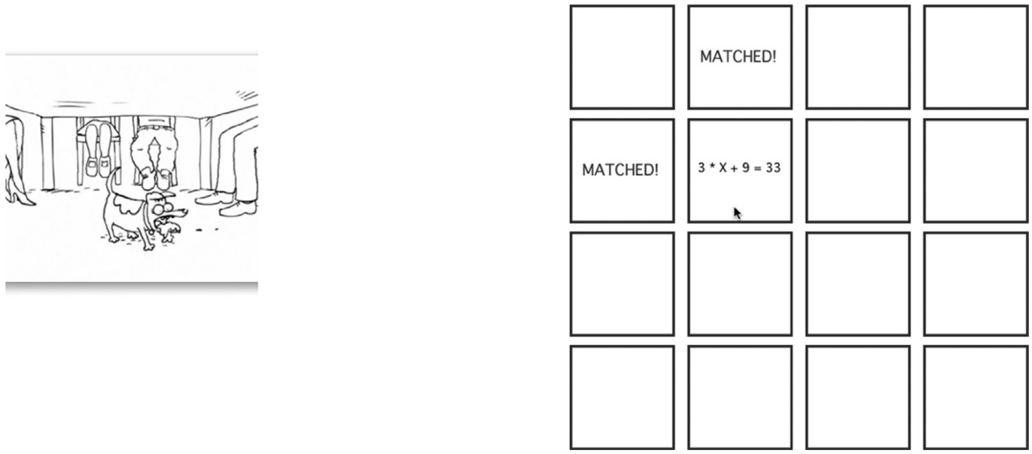

Fig. 13. Hard difficulty level of Experiment 2a. The task (memory game) is on the right and the distractor (cat video) on the left.

drawings and simple stories that are easy to follow at any moment.

Apparatus and Setup Subjects were tested individually in a windowless room. The experiment was presented on an LCD monitor (resolution: 1600 × 1200 pixels, density: 64 pixels/inch), using a chin-rest. The eye tracker was an Eyelink 1000 from SR Research. Eye gaze was measured with a sample rate of 250 Hz. The dimensions of the experimental window were 1200x1300 pixels, while the video was 300 pixels wide. Half of the subjects completed the experiment with the experimental window on the left part of the screen (pixels 0 to 1300) and the other half with the experimental window on the right part of the screen (pixels 300 to 1600; Fig. 13).

Procedure Subjects first practiced one simple memory game (match the numbers) and one Easy level memory game. The real experiment lasted 45 min, one 15 min-block for each difficulty level, with as many memory games as they could fit. When the 15 min were over, subjects finished the memory game they were playing at the moment and could take a break. The order of appearance of each difficulty level was counterbalanced, so that all possible orders would appear equally often. Subjects were informed beforehand that they would complete three blocks of 15 min and were instructed to maximize accuracy. There were no instructions with respect to the video.

6.1.2. Results

Whenever an eye movement crosses the imaginary line between the task side of the screen and the movie side of the screen to the movie side, we define this as the onset of a distraction, and the end of a distraction then when the movement is back over that line. The results show a clear increase in the number of distractions as the task becomes harder (see Fig. 15 where the results are shown together with the model results). We have used the number of distractions, as opposed to the duration of the distractions, because the typical duration of a distraction was very short, around 300 ms (see Appendix for details). Therefore the number of distractions was a better indicator, and can also be better compared to the model. The proportion of fixations on the video compared to task-related fixations was small: 1.5%.

A one-way ANOVA on the log-transformed number of distractions was significant ($F(2,42) = 15.28$, $p < 0.001$). Bonferroni-corrected pairwise comparisons revealed significant ($p < 0.05$) differences between all difficulty levels in both experiments, except between the easy and medium difficulty level.

Even though the task difficulty affected how often subjects were distracted, it did not impact performance: there was no correlation between the number of fixations on the video and the number of memory games completed ($r = 0.08$), nor between the total time spent watching the video and performance ($r = 0.13$). This lack of correlation is consistent with the threaded cognition theory of multitasking: as long as the use of resources between two tasks does not overlap, the tasks do not interfere. Other details on performance can be found in the Appendix.

6.1.3. Model of visual distraction

The operators responsible for visual distraction are identical to the mind-wander operators used in the previous models, except that they are activated by visual input instead of memory, and respond to that input by directing attention to it. The operator that moves attention to the cat-video requires that the visual resource is at that moment available. Similar to the mind-wander operators that target declarative retrieval and working memory, this implements the idea that idle cognitive resources can be hijacked by the distraction process.

For simplicity's sake, we have not constructed a model that plays the whole game, but a model that just solves equations of varying difficulty. We think that this partial model captures the essential characteristics of the task as a whole. Fig. 14 gives a representation of the structure of the model. The hard equations require the sequence as it is shown in Fig. 14, involving 12 operators. The medium

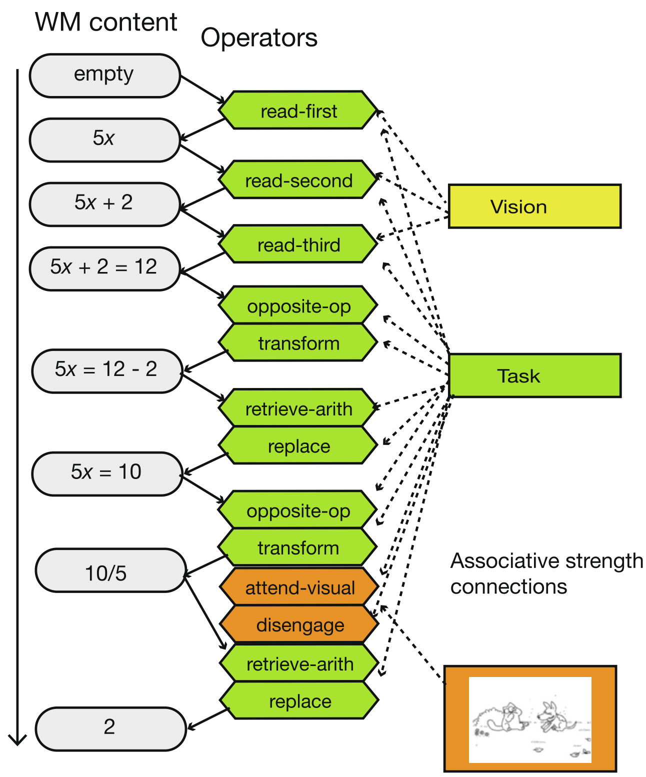

Fig. 14. Example trace of the memory game model with a visual distraction. The distraction is an example, and could have happened after any of the non-visual steps.

and easy equations use the same operators, but omit some of them: the medium equations skip the second transform and arithmetic sequence, and therefore only require 8 operators. The easy equations require no transformations, just the final arithmetic, and one fewer read operator, so a total of 5 operators.

In addition to the task-related operators, the model has two operators that respond to the distraction. The first of these (attend-visual) has as a precondition that the visual resource is not used, and moves attention to the video. The second operator (disengage) activates at the moment that the video is attended, and then disengages immediately in order to return to the main task. This reflects the empirical fact that in the experiment, subjects typically attended the video for only 200–400 ms.

Most of the time, the distraction operators do not have much of a chance to intervene in the equation solving process. When reading operators are engaged they have no chance at all, because the visual resource is in use, whereas a condition for distraction is that the visual resource is free. During the mental operators that follow the reading, the distracting operators have a higher probability to be activated, because the visual resource is not used. In the example this happens between the final transformation and the final arithmetic step.

The model can explain the data, because the distraction operator only competes when the model is mentally solving

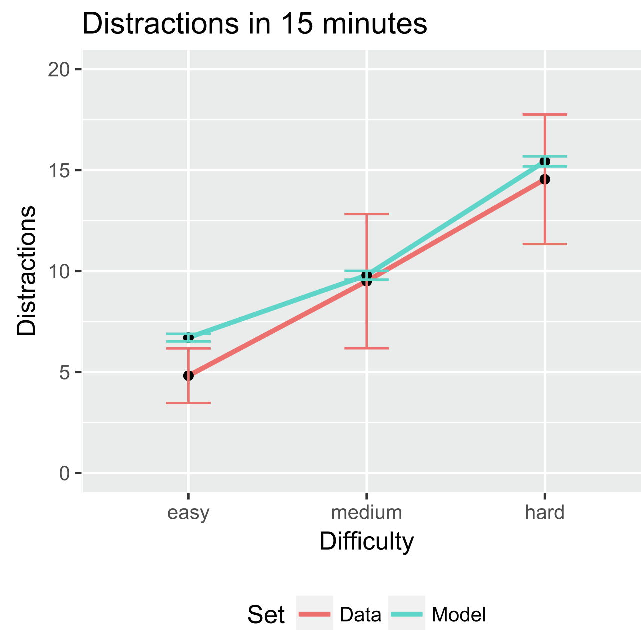

Fig. 15. Results of Experiment 2 and the model simulation.

the equation, which takes proportionally longer as the equation is harder.

6.1.4. Model results

Fig. 15 shows the results of the simulation together with the experimental data. The more difficult the equation-solving task, which crucially relies on the memory resources, the more often the subject is distracted by the cat video.

The critical parameter needed to fit the data is the association strength between the visual stimulus of the cat video and the operator that moves attention to it. Changing that parameter will affect the number of distractions, but will preserve the effect of difficulty, unless it is set so low that the model is never distracted.

7. General discussion

In all three examples discussed in this article, distraction was the result of competition between operators that receive activation from the results of memory retrieval, visual stimuli, working memory, or, in the case of mind-wandering, nothing at all. Distracting operators can only be successful if resources are available to process the distraction. The models do not make a distinction between distraction, mind wandering, or even task-related thought. How we categorize a particular mental operator is not a matter of how it functions as part of the cognitive operators, but rather an attribution that can be made by internal or external evaluation. The same operator that attends to the distracting cat video can also attend a fire alarm, or an alert that is part of the main task.

The kinds of models needed to properly model distraction have to go beyond the traditional "model the task" approach that is common in cognitive modeling. We have to acknowledge that people have many competing goals beyond those given in the instructions of an experiment, and that, particularly in real-life situations, determining what goals to pursue is a major part of cognition. The modeling work presented here only scratches the surface of this issue, because in the three experiments discussed none of the distractions becomes an actual goal itself. But it is easy to see how an operator can elevate a distraction to become a goal. For example, in the visual distraction model, an operator immediately decides not to keep watching the movie after the distraction, because that is most consistent with the data. On the other hand, one can imagine that a subject does decide to watch the movie, build up a representation of the story, and ignore the main task for a while. Such situations may be more likely when the main task has a weaker perceptual component that does not strongly call the subject back to the task, e.g., a detection task for stimuli presented at the perceptual threshold. Also, the experimental paradigm strongly encouraged subjects to stick to the task, whereas in regular life people have more freedom in their choice of goals.

Another challenge for the type of models discussed in this article is that in order to function they need a set of knowledge and experience that is beyond just the knowledge to perform the experimental task. We have assumed that there are patterns of associations between certain words and operators, and certain visual stimuli and operators, but we have not accounted for the mechanisms that build such associations. Anderson and Lebiere (1998) propose a learning mechanism for ACT-R to build associative strength: if a certain memory is retrieved in the context of another memory, the strength of association between those memories is strengthened, a process not unlike Hebb's rule in neural networks (Hebb, 1949). If a particular personality word, say "aggressive" is often followed by an operator that retrieves a relevant episodic memory related to aggressive (in other words, the *wander* operator), then according to that mechanism the strength between that word and the operator is increased (a mechanism similar to what is implemented by context-based memory models such as the Context Maintenance and Retrieval model, Polyn, Norman, & Kahana, 2009). Even with a mechanism like that implemented, the models would require a prior history in which these associations have been learned, clearly an effort with a complexity surpassing the current models. Making explicit models of these mechanisms could allow us to explain how different types of cognitive training affect the tendency to get distracted.

A critical question regarding modeling is to what extent results are dependent on parameter settings in the models. Clearly, the models have several parameters that influence the outcome, in particular the parameters that set the association strengths (the S_{ji}'s), and the parameters that control the amount of spreading activation from each of the buffers (the W_j's). Nevertheless, changes (within reason) in these parameters lead to results that are qualitatively the same, and no alternative settings of parameters can reverse the effects that we model.

The models presented here are in line with explanations of mind-wandering that center on underload, such as Smallwood and Schooler (2006). Interestingly enough, all the tasks we have modeled with the exception of the Smallwood et al. (2011) task are highly engaging tasks. What we have shown is that even in such tasks, some resources are sometimes not used and therefore open to use for other, potentially distracting, uses.

The model is also consistent with Smallwood's notion of perceptual decoupling. The operators that carry out the mind-wandering process (*wander, elaborate*) are associated with each other, making it more likely that mind-wandering continues. Perception is therefore not explicitly blocked during the model's mind-wandering, but nevertheless perception-oriented operators have a lower probability of being chosen. It is also consistent with the cognitive failure theory (McVay & Kane, 2009), because the key to avoiding distraction is to keep the activation of the current goals high enough to block distracting operators. Although we did not explore that idea in the models here, regulatory mechanisms could monitor goal activation, and failure of such mechanisms may lead to increased distraction. This is a failure of *meta*-awareness. The models we built may serve as a mechanistic basis to further support and explore descriptive theories of mind-wandering and distraction. The models also illustrate that it is difficult to resist distraction, because we have no direct control over the selection of the next mental operator. Instead, we can try to influence the competition between operators by strengthening goals, put earplugs in our ears, and turn our heads away from distracting displays. To summarize, the model presented in this article is consistent with existing theories of mind wandering, suggesting that these are not mutually exclusive, but reflect different facets of the phenomenon.

The three examples in this article have not covered all the possible resources that may play a role in distraction. Indeed, the set of resources identified in ACT-R (and, by extension, PRIMs), is certainly incomplete. For example, we can be distracted if we know that we have to leave in 10 min, and periodically check the time (i.e., the temporal resource), or by a sudden touch (i.e., a yet to be defined haptic resource). However, the principles of such distractions should be compatible with the ones outlined in this article.

Although we have not touched upon it, the present model can shed light on the distinction between intentional and unintentional mind wandering (Seli, Risko, Smilek, & Schacter, 2016). ADHD patients report more unintentional mind wandering than non-patients, but their intentional mind wandering is at the same level (Seli, Smallwood, Cheyne, & Smilek, 2015). In addition, mind wandering is more often intentional in easy tasks, but more unintentional in hard tasks (Seli, Risko, & Smilek, 2016). Intentional vs. unintentional can be made explicit in the PRIMs model: if a distraction leads to the setting of a new goal, it is intentional, otherwise it is unintentional. In all the examples we have looked at, distraction remained unintentional, but additional operators could have been added that elevate distraction into a new parallel goal. Such a goal would have an effect that lasts longer than an unintentional distraction, because it keeps activating operators that are not associated with the main task.

Such an account can potentially explain the empirical findings: ADHD patients may be less capable of suppressing operators that are activated through perception and memory retrieval, and therefore are more prone to unintentional mind wandering, but may be equally likely to make the explicit decision to make a distraction into a goal. In addition, someone who is doing an easy task may be more likely to add an additional goal, leading to intentional mind wandering, than someone who is doing a hard task. Similarly, knowing that an important complex task is coming up could lead to more intentional mind-wandering about this upcoming task (Leszczynski et al., 2017).

The theory is probably equally applicable to studies of sustained attention, in which subjects do not take any action for prolonged periods of time, but have to remain vigilant in order to be able to respond quickly to certain situations. In such tasks it is much more likely that distractions turn into parallel goals, and therefore gradually become increasingly strong competitors to the main task. Although the current model does not deal with prolonged periods of task performance, it is easy to see that a vigilance task with little rewards can lose the competition to internal thoughts that are more varied, and therefore potentially more rewarding. Thomson, Besner, and Smilek (2015) account of sustained attention partially overlaps with our theory. Their resource-control theory assumes resources remain constant over time, but the balance between vigilance and mind wandering shifts towards mind wandering over time because executive control cannot keep the vigilance goal active enough. Kurzban, Duckworth, Kable, and Myers (2013) offer a further explanation of this decrease in control: the costs/benefit balance of remaining vigilant decreases over time, making mind wandering increasingly attractive.

To summarize, in this paper we show that mental distraction, mind-wandering and visual distraction can be brought together in a theoretical account that assumes that people always have multiple things on their mind, and that we should start thinking about the way we think in terms of competition between multiple goals and perceptions, rather than a single-track task-focused mind.

8. Author note**a

This research was supported by ERC StG 283597 MULTITASK from the European Research Council. All models discussed in this article can be downloaded from https://github.com/ntaatgen/Distraction. Correspondence concerning this article should be addressed to Niels Taatgen, University of Groningen, Bernoulli Institute, Nijenborgh 9, 9747 AG Groningen, Netherlands, Email: n.a.taatgen@rug.nl.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix A. Additional results

Experiment 1a

In experiment 1a, subjects were faster on the control processing task (mean 0.82, sd 0.12) then in the SRP task (mean 1.00, sd 0.21), a difference that is significant (paired *t*-test, $t(27) = 6.87$, $p < 0.001$). Table A.1 lists the mixed-effects models that we fitted on the partial-credit scores

Table A1
Mixed-effects model analyses of the impact of average processing time within a trial on partial-credit score for Experiment 1a and 1b, separated by condition.

Experiment/ Condition	Factor	Estimate	SE	z-value	p-value
1a/Control	Intercept	7.127	0.925	7.76	
	Processing time	−4.049	0.620	−6.54	<0.001
	Span	−0.170	0.169	−1.01	0.314
1a/SRP	Intercept	5.153	0.755	6.82	
	Processing time	−1.340	0.456	−2.94	0.003
	Span	−0.347	0.127	−2.73	0.006
1b/Control	Intercept	7.223	1.152	6.27	
	Processing time	−3.630	0.801	−4.53	<0.001
	Span	−0.238	0.213	−1.12	0.263
1b/SRP	Intercept	6.635	0.909	7.30	
	Processing time	−1.202	0.400	−3.00	0.003
	Span	−0.709	0.174	−4.08	<0.001

Table A2
Performance on the memory task in Experiment 2 (1 standard error in parentheses).

	Easy	Medium	Hard
Average time per memory game (sec)	48.02 (2.46)	87.15 (6.32)	240.0 (19.11)
Number of memory games completed in 15 min	19.09 (0.86)	11.23 (0.63)	4.68 (0.37)

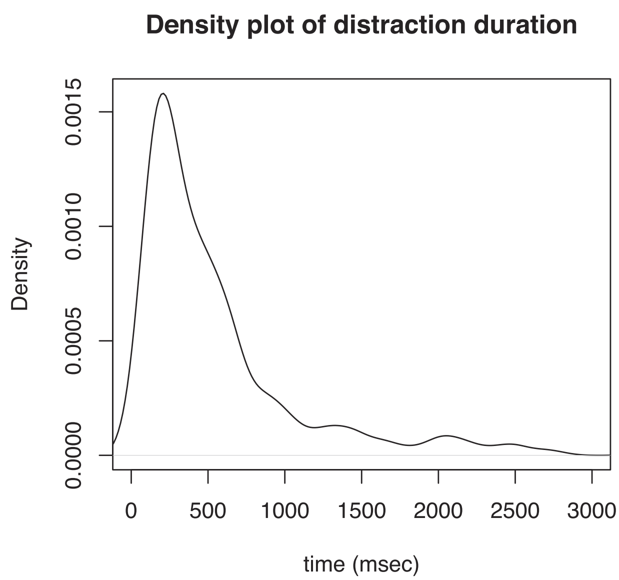

Fig. A1. Density plot of distraction duration in Experiment 2.a.

for each of the conditions with processing time per item and span as fixed effects.

Experiment 1b

In experiment 1b, subjects were faster on the control processing task (mean 0.76, sd 0.090) then in the SRP task (mean 0.92, sd 0.15), a difference that is significant (paired *t*-test, $t(20) = 5.7$, $p < 0.001$). Table A.1 lists the mixed-effects models that we fitted on the partial-credit scores for each of the conditions with processing time per item and span as fixed effects.

Given that the SRP words appeared several times in the experiment, we were able to check whether subjects scored them consistently. The average consistency was high, M = 0.826, SD = 0.128, where 0 is random behavior, and 1.0 is consistently giving the same answer on each item. On average subjects scored words as applicable to them with a proportion of 0.506 (SD = 0.04), which is approximately half the items.

Experiment 2

Table A.2 lists the performance of subjects on the memory task. As expected, they took more time to solve the harder memory games.

The duration of the distractions was typically very short. Fig. A.1 shows a density plot of the looking times at the cat video, which peaks at around 300 ms.

References

Altmann, E. M., & Trafton, J. G. (2002). Memory for goals: An activation-based model. *Cognitive Science, 26*, 39–83.

Anderson, J. R. (2007). *How can the human mind occur in the physical universe?*. New York: Oxford University Press.

Anderson, J. R., Fincham, J. M., Schneider, D. W., & Yang, J. (2012). Using brain imaging to track problem solving in a complex state space. *NeuroImage, 60*(1), 633–643. https://doi.org/10.1016/j.neuroimage.2011.12.025.

Anderson, J. R., & Lebiere, C. (1998). The atomic components of thought. book, Mahwah, NJ: Erlbaum.

Barnhofer, T., Crane, C., Spinhoven, P., & Williams, J. M. G. (2007). Failures to retrieve specific memories in previously depressed individuals: Random errors or content-related?. *Behaviour Research and Therapy, 45*(8), 1859–1869. https://doi.org/10.1016/j.brat.2007.02.006.

Bastian, M., & Sackur, J. (2013). Mind wandering at the fingertips: Automatic parsing of Subjective states based on response time Variability. *Frontiers in Psychology, 4*, 573. https://doi.org/10.3389/fpsyg.2013.00573.

Borst, J. P., Taatgen, N. A., Stocco, A., & van Rijn, H. (2010). The Neural Correlates of Problem States: Testing fMRI Predictions of a Computational Model of Multitasking. *PLoS ONE, 5*(9), article.

Borst, J. P., Taatgen, N. A., & van Rijn, H. (2010). The Problem State: A Cognitive Bottleneck in Multitasking. *Journal of Experimental Psychology Learning, Memory, and Cognition, 36*(2), 363–382.

Botvinick, M. M., Braver, T. S., Barch, D. M., Carter, C. S., & Cohen, J. D. (2001). Conflict monitoring and cognitive control. *Psychological Review, 108*(3), 624–652.

Christoff, K., Irving, Z. C., Fox, K. C. R., Spreng, R. N., & Andrews-Hanna, J. R. (2016). Mind-wandering as spontaneous thought: A dynamic framework. *Nature Reviews Neuroscience*. https://doi.org/10.1038/nrn.2016.113.

Conway, A. R. A., Kane, M. J., Bunting, M. F., Hambrick, D. Z., Wilhelm, O., & Engle, R. W. (2005). Working memory span tasks: A methodological review and user's guide. *Psychonomic Bulletin & Review, 12*(5), 769–786. https://doi.org/10.3758/BF03196772.

D'Argembeau, A., Ruby, P., Collette, F., Degueldre, C., Balteau, E., Luxen, A., ... Salmon, E. (2007). Distinct Regions of the Medial Prefrontal Cortex Are Associated with Self-referential Processing and Perspective Taking. *Journal of Cognitive Neuroscience, 19*(6), 935–944. https://doi.org/10.1162/jocn.2007.19.6.935.

Dixon, P., & Bortolussi, M. (2013). Construction, integration, and mind wandering in reading. *Canadian Journal of Experimental Psychology/Revue Canadienne de Psychologie Expérimentale, 67*(1), 1–10. https://doi.org/10.1037/a0031234.

Forster, S., & Lavie, N. (2014). Distracted by your mind? Individual differences in distractibility predict mind wandering. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 40*(1), 251–260. https://doi.org/10.1037/a0034108.

Franklin, M. S., Smallwood, J., & Schooler, J. W. (2011). Catching the mind in flight: Using behavioral indices to detect mindless reading in

real time. *Psychonomic Bulletin & Review, 18*(5), 992–997. https://doi.org/10.3758/s13423-011-0109-6.
Friendly, M., Franklin, P. E., Hoffman, D., & Rubin, D. C. (1982). The Toronto Word Pool: Norms for imagery, concreteness, orthographic variables, and grammatical usage for 1,080 words. *Behavior Research Methods and Instrumentation, 14*, 375–399.
Giambra, L. M. (1989). Task-unrelated thought frequency as a function of age: A laboratory study. *Psychology and Aging, 4*(2), 136–143. https://doi.org/10.1037/0882-7974.4.2.136.
Goldberg, L. R. (1992). The development of markers for the Big-Five factor structure. *Psychological Assessment, 4*(1), 26–42. https://doi.org/10.1037/1040-3590.4.1.26.
Hockey, G. R. J. (1997). Compensatory control in regulation of human performance under stress and high workload: A cognitive-energetical framework. *Biological Psychology, 45*, 73–93.
Hebb, D. O. (1949). Organization of Behavior. book, New York: Wiley.
Katidioti, I., Borst, J. P., & Taatgen, N. A. (2014). What happens when we switch tasks: Pupil dilation in multitasking. *Journal of Experimental Psychology: Applied, 20*(4), 380–396. https://doi.org/10.1037/xap0000031.
Katidioti, I., Borst, J. P., Van Vugt, M. K., & Taatgen, N. A. (2016). Interrupt me: External interruptions are less disruptive than self-interruptions. *Computers in Human Behavior, 63*, 906–915. https://doi.org/10.1016/j.chb.2016.06.037.
Katidioti, I., & Taatgen, N. A. (2014). Choice in Multitasking: How Delays in the Primary Task Turn a Rational Into an Irrational Multitasker. *Human Factors: The Journal of the Human Factors and Ergonomics Society, 56*(4), 728–736. https://doi.org/10.1177/0018720813504216.
Klinger, E., Gregoire, K. C., & Barta, S. G. (1973). Physiological correlates of mental activity: Eye movements, alpha, and heart rate during imag- ining, suppression, concentration, search, and choice. *Psychophysiology, 10*, 471–547.
Kurzban, R., Duckworth, A., Kable, J. W., & Myers, J. (2013). An opportunity cost model of subjective effort and task performance. *Behavioral and Brain Sciences, 36*(6), 661–679.
Laird, J. E., Newell, A., & Rosenbloom, P. S. (1987). Soar: An architecture for general intelligence. *Artificial Intelligence, 33*(1), 1–64.
Lavie, N. (2005). Distracted and confused?: Selective attention under load. *Trends in Cognitive Sciences, 9*(2), 75–82. https://doi.org/10.1016/j.tics.2004.12.004.
Lavie, N., & de Fockert, J. W. (2006). Frontal control of attentional capture in visual search. *Visual Cognition, 14*, 863–876. https://doi.org/10.1080/13506280500195953.
Leszczynski, M., Chaieb, L., Reber, T. P., Derner, M., Axmacher, N., & Fell, J. (2017). Mind wandering simultaneously prolongs reactions and promotes creative incubation. *Scientific Reports, 7*, 10197. https://doi.org/10.1038/s41598-017-10616-3.
McVay, J. C., & Kane, M. J. (2009). Conducting the train of thought: Working memory capacity, goal neglect, and mind wandering in an executive-control task. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 35*(1), 196–204. https://doi.org/10.1037/a0014104.
McVay, J. C., & Kane, M. J. (2010). Does mind wandering reflect executive function or executive failure? Comment on Smallwood and Schooler (2006) and Watkins (2008). *Psychological Bulletin, 136*(2), 188–197. https://doi.org/10.1037/a0018298.
Meyer, D. E., & Kieras, D. E. (1997). A computational theory of executive cognitive processes and multiple-task performance: Part I. *Basic mechanisms. Psychological Review, 104*(1), 3–65. https://doi.org/10.1037/0033-295X.104.1.3.
Nijboer, M., Borst, J. P., van Rijn, H., & Taatgen, N. A. (2016). Driving and Multitasking: The Good, the Bad, and the Dangerous. *Frontiers in Psychology, 7*, 1718. https://doi.org/10.3389/fpsyg.2016.01718.
Peirce, J. W. (2007). PsychoPy—Psychophysics software in Python. *Journal of Neuroscience Methods, 162*(1), 8–13. https://doi.org/10.1016/j.jneumeth.2006.11.017.
Polyn, S. M., Norman, K. A., & Kahana, M. J. A. (2009). Context maintenance and retrieval model of organizational processes in free recall. *Psychological Review, 116*(1), 129–156.
Posner, M. I., & Petersen, S. E. (1990). The attention system of the human brain. *Annual Review of Neuroscience, 13*, 25–42. https://doi.org/10.1146/annurev.ne.13.030190.000325.
Redick, T. S., Broadway, J. M., Meier, M. E., Kuriakose, P. S., Unsworth, N., Kane, M. J., & Engle, R. W. (2012). Measuring Working Memory Capacity With Automated Complex Span Tasks. *European Journal of Psychological Assessment, 28*(3), 164–171. https://doi.org/10.1027/1015-5759/a000123.
Salvucci, D. D., & Macuga, K. L. (2002). Predicting the effects of cellular-phone dialing on driver performance. *Cognitive Systems Research, 3*(1), 95–102. https://doi.org/10.1016/S1389-0417(01)00048-1.
Salvucci, D. D., & Taatgen, N. A. (2008). Threaded cognition: An integrated theory of concurrent multitasking. *Psychological Review, 115*(1), 101–130.
Schooler, J. W., & Schreiber, C. A. (2004). Experience, meta-consciousness, and the paradox of introspection. *Journal of Consciousness Studies, 11*, 17–39.
Schooler, J. W., Smallwood, J., Christoff, K., Handy, T. C., Reichle, E. D., & Sayette, M. A. (2011). Meta-awareness, perceptual decoupling and the wandering mind. *Trends in Cognitive Science, 15*, 319–326.
Seli, P., Risko, E. F., & Smilek, D. (2016). On the necessity of distinguishing between unintentional and intentional mind wandering. *Psychological Science, 27*(5), 685–691.
Seli, P., Risko, E. F., Smilek, D., & Schacter, D. L. (2016). Mind-wandering with and without intention. *Trends in Cognitive Sciences, 20*(8), 605–617.
Seli, P., Smallwood, J., Cheyne, J. A., & Smilek, D. (2015). On the relation of mind wandering and ADHD symptomatology. *Psychological Bulleting and Review, 22*, 629–636.
Smallwood, J. (2013). Distinguishing how from why the mind wanders: A process-occurrence framework for self-generated mental activity. *Psychological Bulleting, 139*(3), 519–535.
Smallwood, J., Brown, K. S., Tipper, C., Giesbrecht, B., Franklin, M. S., Mrazek, M. D., ... Schooler, J. W. (2011). Pupillometric Evidence for the Decoupling of Attention from Perceptual Input during Offline Thought. *PLoS ONE, 6*(3). https://doi.org/10.1371/journal.pone.0018298 e18298.
Smallwood, J., Nind, L., & O'Connor, R. C. (2009). When is your head at? An exploration of the factors associated with the temporal focus of the wandering mind. *Consciousness and Cognition, 18*(1), 118–125. https://doi.org/10.1016/j.concog.2008.11.004.
Smallwood, J., & Schooler, J. W. (2006). The restless mind. *Psychological Bulletin, 132*, 946–958.
Smallwood, J., & Schooler, J. W. (2015). The Science of Mind Wandering: Empirically Navigating the Stream of Consciousness. *Annual Review of Psychology, 66*(1), 487–518. https://doi.org/10.1146/annurev-psych-010814-015331.
Smallwood, J., Schooler, J. W., Turk, D. J., Cunningham, S. J., Burns, P., & Macrae, C. N. (2011). Self-reflection and the temporal focus of the wandering mind. *Consciousness and Cognition, 20*(4), 1120–1126. https://doi.org/10.1016/j.concog.2010.12.017.
Strayer, D. L., & Johnston, W. A. (2001). Driven to distraction: Dual-Task Studies of Simulated Driving and Conversing on a Cellular Telephone. *Psychological Science, 12*(6), 462–466.
Sui, J., & Humphreys, G. W. (2015). The Integrative Self: How Self-Reference Integrates Perception and Memory. *Trends in Cognitive Sciences, 19*(12), 719–728. https://doi.org/10.1016/j.tics.2015.08.015.
Taatgen, N. A. (2013). The nature and transfer of cognitive skills. *Psychological Review, 120*, 439–471.
Thomson, D. R., Besner, D., & Smilek, D. (2015). A Resource-Control Account of Sustained Attention : Evidence From Mind-Wandering and Vigilance Paradigms. *Perspectives on Psychological Science, 10*(1), 82–96. https://doi.org/10.1177/1745691614556681.

VandeKerckhove, J. A., & Tuerlinckx, F. (2007). Fitting the Ratcliff diffusion model to experimental data. *Psychonomic Bulletin & Review, 14*(6), 1011–1026.

Wessel, I., Postma, I. R., Huntjens, R. J. C., Crane, C., Smets, J., Zeeman, G. G., & Barnhofer, T. (2014). Differential correlates of autobiographical memory specificity to affective and self-discrepant cues. *Memory, 22*(6), 655–668. https://doi.org/10.1080/09658211.2013.811255.

Wickens, C. D. (2002). Multiple resources and performance prediction. *Theoretical Issues in Ergonomics Science, 3*(2), 159–177. https://doi.org/10.1080/14639220210123806.

Wickens, C. D. (2008). Multiple Resources and Mental Workload. *Human Factors, 50*(3), 449–455. https://doi.org/10.1518/001872008X288394.