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The wandering self: Tracking distracting self-generated thought in a cognitively demanding context

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ABSTRACT

We investigated how self-referential processing (SRP) affected self-generated thought in a complex working memory task (CWM) to test the predictions of a computational cognitive model. This model described self-generated thought as resulting from competition between task- and distracting processes, and predicted that self-generated thought interferes with rehearsal, reducing memory performance. SRP was hypothesized to influence this goal competition process by encouraging distracting self-generated thinking. We used a spatial CWM task to examine if SRP instigated such thoughts, and employed eye-tracking to examine rehearsal interference in eye-movement and self-generated thinking in pupil size. The results showed that SRP was associated with lower performance and higher rates of self-generated thought. Self-generated thought was associated with less rehearsal and we observed a smaller pupil size for mind wandering. We conclude that SRP can instigate self-generated thought and that goal competition provides a likely explanation for how self-generated thoughts arises in a demanding task.

1. Introduction

When we try to characterize our conscious experience, we can say that is guided in roughly two ways (see Dixon, Fox, & Christoff, 2014). On one hand, our thoughts are shaped by what we perceive in our external environment. For instance, when we are reading a book, our thoughts are likely on what we read. On the other hand, our conscious experience is not always tied to our environment. Analogously, we might find ourselves thinking about future plans while reading this article. Or: we might contemplate about the answer to a question we just received. In these situations, constructive and associative processes in memory shape our thoughts internally without the need of perceptual guidance.

This internally directed thought, or *self-generated thought*, has been extensively studied in past recent years with examples including: thinking about the self or others, mental simulations, imagination, past and future thinking, and planning (for a review see Andrews-Hanna, Smallwood, & Spreng, 2014). Self-generated thought can occur both in the absence and the presence of external stimuli. In addition, it can be triggered both by internal and external influences, but it always involves a disengagement from the external environment (Schooler et al., 2011). In this article, we will focus on self-generated thought that occurs in the context of a main external task but is not relevant to performance on this task. In other words, we want to explore self-generated thought that becomes a distraction from the main task.

One popular example of self-generated thought, oftentimes regarded as a distraction from main activities, is *mind wandering*. Mind wandering refers to a self-generated thought process that proceeds independently of an external task (Smallwood & Schooler, 2015). Since mind wandering is covert in nature, it can only be observed indirectly with self-report questions that sample thought content

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(see Csikszentmihalyi & Larson, 1987; Larson & Csikszentmihalyi, 1983). These self-report questions, or *thought-probes*, are embedded in the task to determine how mind wandering is related to performance on the task. Studies using thought-probes have identified that mind wandering is associated with higher and more variable response times (e.g., Bastian & Sackur, 2013; van Vugt & Broers, 2016) and to decrements in task performance (e.g., working memory; Rummel & Boywitt, 2014). Although mind wandering has clear adverse consequences for our current activities, this does not need to be true for tasks still in the future. The content of mind wandering has been found adaptive in many instances, with thoughts that are highly self-focused, goal-directed, and future oriented (see Baird, Smallwood, & Schooler, 2011).

Until recently, most studies have examined mind wandering in tasks imposing low cognitive demand, allowing cognitive resources for mind wandering to occur. However, one might argue that it is more interesting to investigate mind wandering (and also other self-generated thoughts) in contexts where one is busily engaged in a task, situations where performance on main activities is at stake. Research has shown that the adverse consequences of mind wandering are greater in tasks with higher cognitive demand (such as in n-back and general intelligence measures; see McVay & Kane, 2012a, 2012b; Mrazek et al., 2012; Rummel & Boywitt, 2014; Smallwood & Andrews-Hanna, 2013). Commonly, it is observed that mind wandering is less frequent in higher demand contexts (see e.g., Smallwood, Brown et al., 2011; Smallwood, Schooler et al., 2011; Thomson, Besner, & Smilek, 2013), but proportions are still substantial. Recent work by Seli, Risko, and Smilek (2016) even found equal rates of mind wandering across task demand, with relatively more reports of unintentional mind wandering in a challenging task and more intentional mind wandering in an easier task. Similar to what has been found for lower demand contexts, the content of mind wandering is predominantly self-related and focused on personal goals and future plans (Smallwood, Schooler et al., 2011). Consequently, these results suggest that mind wandering, and potentially self-generated thought in general, has similar characteristics in contexts of low and high cognitive demand.

In the present study, we will focus on demanding task paradigms to examine self-generated thought in a context where it becomes a distraction for a main task. Building on earlier work (viz., Daamen, Van Vugt, & Taatgen, 2016), we are interested in investigating the potential of self-referential processing to instigate such thoughts. Our approach is to test the assumptions of a computational cognitive model, which describes the cognitive processes of participants in a task and predicts how self-generated thought can occur in short spare moments of a task. We will test whether self-generated thought occurs in spare moments of the task by means of triangulating eye-tracking measures and thought-probes. However, before explaining the full details of our experiment, we will first provide a short review on correlates of self-generated thought in eye-tracking measurements. Subsequently, we will discuss the role of self-referential processing in instigating self-generated thought.

1.1. Correlates of self-generated thought in eye-tracking

The thought-probes we just introduced have the advantage to provide insight in the content of self-generated thought. However, the discrete nature of the measure makes it hard to determine when the thoughts occurred. Correlates in physiological or task performance measures (e.g., response times) can provide this knowledge and may allow us to track self-generated thought online (e.g., Franklin, Smallwood, & Schooler, 2011; Grandchamp, Braboszcz, & Delorme, 2014; Mittner et al., 2014). Here we will review studies using eye-movement and pupil size measurement, since these are the measures we will use in our current study.

With eye-tracking we continuously measure eye-movement and pupil size throughout an experiment while having the advantage of being entirely unobtrusive (unlike e.g., fMRI and EEG). Eye-movement correlates of self-generated thought have commonly been investigated in linguistics studies, in which this measure is employed to examine real-time cognitive processing during reading (e.g., Reichle, Reineberg, & Schooler, 2010; Uzzaman & Joordens, 2011). For instance, a recent study by Foulsham, Farley, and Kingstone (2013) found that participants showed longer and slightly more frequent fixations in sentence reading during mind wandering. According to the researchers, the longer fixation duration are a result of a decoupling between seeing the words and processing their meaning, which provides evidence for the idea that self-generated thought, such as mind wandering, involves a disengagement of attention from the external task (see Kam & Handy, 2013).

Similar results were found in a recent study by Benedek, Stoiser, Walcher, and Körner (2017). The researchers examined the influence of self-generated thought (called internally-directed cognition in their study) on eye-movement and pupillometric measures by manipulating the focus of attention (internal and external) with an externally demanding task (sentence generation) and an internally demanding task (anagram). The rationale was that the anagram task would require self-generated thought to solve, building on an internal representation of the problem. The sentence generation task, however, could be solved without. The researchers found that self-generated thought was associated with fewer fixations and saccades, but with increased fixation duration. Based on the results, the researchers conclude that eye-movements are more spontaneous and less directed during self-generated thought. In addition to eye-movement differences, they also identified a larger average pupil size for self-generated thought, indicating higher levels of arousal (see Gilzenrat, Nieuwenhuis, Jepma, & Cohen, 2010; Murphy, Robertson, Balsters, & O'Connell, 2011). Potentially, the higher levels of arousal reflected the decoupling of attention from the external task, which is hypothesized to occur with self-generated thought.

Research on pupil size correlates for mind wandering has not been fully consistent. Similar to the above-mentioned study of Benedek, some studies have identified larger pupil sizes prior to reports of mind wandering (Franklin, Broadway, Mrazek, Smallwood, & Schooler, 2013; Smallwood et al., 2012; Smallwood, Brown et al., 2011), whereas other studies have found smaller pupil sizes (e.g., Grandchamp et al., 2014; Konishi, Brown, Battaglini, & Smallwood, 2017; Mittner et al., 2014; Unsworth & Robison, 2016). Explanations for these mixed results are speculative. Notable about the above mentioned studies is that larger pupil sizes during mind wandering episodes were primarily found in relatively undemanding tasks (e.g., reading) whereas the smaller pupil sizes were identified in more demanding tasks (e.g., n-back). In more difficult tasks, mind wandering may result in a lower arousal state

compared to on-task thoughts, resulting in a relatively smaller pupil size. Easier tasks are known to engender more future oriented and intentional mind wandering, which may be associated with higher levels of arousal.

In conclusion, self-generated thought is not unequivocally associated with patterns in eye-movement and pupil size. Tasks without external stimuli show less but more spontaneous eye-movements, whereas tasks with higher visual demand (e.g., reading) show more frequent eye-movements. Self-generated thought seems to be associated with smaller pupil sizes in task with relatively high cognitive load, but with larger pupil sizes in tasks with lower load.

1.2. Prior work: Instigating self-generated thought in a complex working memory task

In the present study, we want to extend on earlier work (viz., Daamen et al., 2016), in which we assessed self-generated thought in a demanding task and demonstrated that when participants were asked to think about themselves, performance on a memory task decreased compared to when they made simple semantic judgments. We came to this understanding by using a variation on a verbal complex working memory task (CWM). In such a task, participants have to memorize items (i.e., letters) while also performing a processing task between each presented item. We assumed that the processing task blocked any rehearsal processes. Therefore in order to do well in this task, a good strategy would be to squeeze in rehearsals whenever this was possible. One moment during which rehearsal would be possible was a 1-s blank period that followed the processing task. However, if the processing task evoked distracting self-generated thoughts, these may have been pursued in the blank instead.

The frequency of self-generated thought was manipulated by introducing a self-referential processing (SRP) task in the paradigm. Processing self-related information is known to evoke highly automatic elaboration processes in autobiographical memory (e.g., Sui & Humphreys, 2015; Wessel et al., 2014), which might also trigger mind wandering through spontaneous associations with e.g. personal goals or aspirations (see Barnhofer, Crane, Spinhoven, & Williams, 2007; D'Argembeau et al., 2007; Klinger & Cox, 2004). We contrasted the self-referential processing condition with a control condition in which participants had to decide whether a depicted object fitted in a shoebox. The results of our study showed worse memory performance for the self-referential processing condition compared to the shoebox condition.

1.2.1. Computational cognitive model of distracting self-generated thought

We predicted that the reduction in memory performance in the self-referential processing condition was the result of increased elaboration of the processing words and mind wandering during the blank periods. To formalize this prediction, we previously built a computational cognitive model of the task in the PRIMs cognitive architecture (Taategen, 2013; see also Hiatt & Trafton, 2015; van Vugt, Taategen, Sackur, & Bastian, 2015, for other models of mind wandering). PRIMs describes cognition in terms of interactions and exchange of information between multiple cognitive resources (i.e., vision, motor, working memory, long-term memory, and control). This information sharing process is controlled via operators, which are small rule-based operations that work towards a shared goal. For instance, our model (see Fig. 1) has an operator that stores a target item in working memory, and another operator to retrieve it for recall. A fully working model requires several of these operators to complete a task and uses a selection process to find the right operator at the right time. This selection process is based on the priority (i.e., an 'activation' value) of the operator and can be influenced by the content of the cognitive resources. Competition between operators during the selection process and the influence of the content of the cognitive resource in this competition, are the key mechanism of our model.

Following existing literature on the influence of processing self-related information and memory systems (see Self-Memory System theory; Conway & Pleydell-Pearce, 2000), we expected that the task could elicit two 'types' of self-generated thought. First of all, self-generated thought may appear as *mental-elaboration* on the word stimuli from the processing task, which means that participants will resume thinking about their decisions. These mental elaborations are created by spontaneous elaboration processes in memory, which have been implicated with self-referential processing (e.g., Sui & Humphreys, 2015; Wessel et al., 2014). And secondly, the self-related material may instigate *mind wandering* by means of evoking spontaneous associations with e.g. concerns or personal goals. Both types of self-generated thought are triggered by the task, but rely on internal representations in memory for their continuity. The content of mental-elaboration is mostly related to the task, whereas mind wandering is task-unrelated. Irrespective of task-(un) relatedness, we argue that both are irrelevant to performance on the task since engaging in them during blank periods will interfere with rehearsal of the targets.

Despite the fact that we expected two different manifestations of self-generated thought, our current model does not distinguish between different types. The reason for this is that we were primarily interested in modeling when and why self-generated thought may occur, and not so much about modeling the phenomenology of the thought processes.

We modeled both manifestations of self-generated thought with the same two operators that control the elaboration on the words from the processing task and possible further associations. These operators do not belong to the task itself, and have therefore little priority. However, when self-related information enters the cognitive resource of vision and/or the working memory, it can temporarily increase the priority of operators that control self-generated thought. Eventually, the model will start to engage in self-generated thought because the priority of its operators will have become high enough to allow them to be selected. The chances of this happening are lower for the control condition because the words during this processing task do not increase the priority of the operators for self-generated thought since they do not prompt the elaboration process (dark blue shapes in Fig. 1).

So how can this model explain the performance decrement for the self-referential processing condition? As described above, the verbal CWM task has a short 1-s break (i.e., blank period) following the processing task. During this break, we assumed that participants would rehearse the items of the CWM task, as rehearsal was difficult to perform in the rest of the trial. However, it could also be an opportunity for e.g. mind wandering. The model behaves similarly. During the break, the model can choose between its task

Fig. 1. Overview of the Primitive Elements of Skill (PRIMs) model of self-generated thought in a complex working memory task. WM refers to working memory. Decl. Memory refers to declarative memory/long-term memory. The self-generated thought processes are mediated by the 'wander' and 'elaborate' operators (in dark blue). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.) (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

goal to rehearse the items or to select self-generated thought operators. Because these operators have a higher priority in the self-referential processing condition, the model is more likely to engage in self-generated thought during this spare moment in the task. Consequently, the model does not rehearse and will most likely forget some target items. The result is that the model will perform relatively worse when it is experiencing self-generated thought, thereby producing the performance decrement observed in the behavioral data.

1.3. Current study

The main goal of the present study is to investigate whether self-referential processing can influence the propensity to self-generated thoughts that are irrelevant to performance in a demanding complex working memory task. For this purpose we tested the assumption of our computational cognitive model, which posits that self-referential processing is a strong competitive process, capable of triggering self-generated thought during spare moments of the task (i.e., blank periods) at a cost for rehearsal. We included thought-probes to measure thought directly, allowing us to examine whether participants were rehearsing the targets (i.e., *on-task*) or not (i.e., *off-task*) and whether self-generated thinking increased in the self-referential processing condition. We also used eye-tracking to provide additional measures to the thought-probes. By combining both self-report and physiological measures we could give a more objective account of self-generated thought in the blank periods of the task, without being solely dependent on one measuring technique.

We re-designed the verbal CWM from Daamen et al. (2016) into a spatial version with locations as target items instead of letters, allowing us to track rehearsal (or the absence thereof) with an eye-tracker. Memory researchers have found that rehearsal of spatial locations is accompanied with eye-movements to these locations (see e.g., Logie, 1995). We assumed that rehearsals mediated by eye-movements would take more time to perform compared to the verbal rehearsals in Daamen et al. (2016). Therefore, we also extended the duration of the blank period from 1 s to 2 s. Fixations to locations of the to-be-memorized targets were interpreted as an effort to rehearse the targets. We hypothesized that there would be fewer fixations on target locations for the self-referential processing condition compared to control, reflecting that self-generated thought (i.e., mental-elaboration and mind wandering) interfered with rehearsal (see Benedek et al., 2017).

With respect to the pupil size measurements, we hypothesized that episodes of mind wandering would be associated with smaller pupil sizes (see Grandchamp et al., 2014; Konishi & Smallwood, 2016; Mittner et al., 2014; Unsworth & Robison, 2016). We had no clear hypothesis about the pupil size for incidences of mental-elaboration. Since we expected more mind wandering to occur in self-

referential processing trials compared to control trials, we hypothesized we would find smaller average pupil sizes in self-referential processing trials compared to control.

For both eye-movement and pupil size, we focused on the blank periods following the processing task. These periods were expected to show most rehearsal and self-generated thought as it was predicted by the model to show most competition since the task does not give either of the two goals a clear preference.

2. Material and methods

2.1. Participants

A total of 38 native Dutch speakers participated in this study. All participants were screened for having normal or corrected-to-normal vision and received a small monetary compensation as reward. We excluded the data of 1 participant from the analysis as this participant performed close to chance level on the processing task in the control condition, which suggests that this participant did not perform the processing task seriously. Another 5 participants were removed after we found through visual inspection of the eye-tracking data that there was excessive data loss (i.e., > 20% of missing data and loss of data in multiple consecutive trials). This left us with a final sample of 32 participants (18 female, $M_{age} = 22.4$, $SD_{age} = 2.6$). All experiments were conducted in accordance with the Declaration of Helsinki, and all participants signed an informed consent form prior to the start of the experiment.

2.2. Apparatus

The participants were tested in a small windowless room at the University of Groningen. This room contained a chair, a desk on which the computer and the eye-tracker were located, and a chin-rest attached to the desk. The experiment was presented on a 20 in. LCD-monitor (1600 × 1200, 64 PPI) and was positioned approximately 60 cm from the chin-rest (SR-Research Head Support).

In order to measure eye movement and pupil size, we used an Eyelink 1000 eye-tracker from SR Research, which was capable of measuring gaze position at a spatial resolution of < .001° RMS and pupil size at 0.2% of the diameter. The sampling rate was set at 250 z.

The stimulus presentation was controlled with PsychoPy (Peirce, 2007). Before the start of the experiment, a 9-point calibration was performed using the software of the eye-tracker. We performed no additional calibrations during the experiment, unless the eye-tracker frequently lost track of the pupil. Re-calibration for this reason was necessary for 5 of our participants, of which two participants were in the end excluded from analysis (the two participants are included in the five mentioned in section *Participants*).

2.3. Materials and design

In the interest of tracking mind wandering and rehearsal, we examined pupil size and eye movement (fixations) in a spatial variant of the complex working memory task (see Fig. 2). Our task required participants to memorize the locations of target items (an 'X', Helvetica font, 40 pixels in height) in a 4 × 4 matrix in sequential order, while also performing a processing task after each presented target item. Similar to our previous work (Daamen et al., 2016), the processing task involved evaluating words corresponding two separate conditions. In the control condition, nicknamed 'shoebox', participants were presented with object words (Helvetica font, 30 pixels in height) in the same 4 × 4 matrix and decided whether the depicted object fitted in a shoebox. All the selected words in this condition were written in Dutch and contained no examples of objects with negative valence (e.g., knife,

Fig. 2. Overview of one trial in the spatial version of the complex working memory task used in this experiment. The trial in this figure represents a self-referential processing condition trial. The diagonal arrow shows the progression of a trial in time.

needle, bullet). The experimental self-referential condition required the participants to evaluate whether a presented personality trait (e.g., kind) described them ('Am I kind?'). For both conditions we used the same word set as the study of Daamen.

We used a grey background (120,120,120; rgb255) for the entire experiment including calibration. The stimuli and instructions were presented in black (0,0,0; rgb255) and the matrix surrounding the stimuli had an intermediate color (85,85,85; rgb255) between the grey background and the black stimuli.

2.3.1. Thought-probe question

Throughout the experiment, the participants were periodically presented with thought-probes following recall (see Fig. 2). These thought-probes were used to sample thought content during the blank period prior to recall.

The question we used was a variant of the thought-probe introduced by Stawarczyk, Majerus, Maj, Van der Linden, and D'Argembeau (2011) and Unsworth and Robison (2016). The question was (translated from Dutch), 'What were you thinking about before you were prompted to answer?', with the following response options: (1) I tried to remember the location of the X's; (2) I was still thinking about the words from the decision task (= processing task); (3) I was evaluating aspects of the task (e.g., my performance, how long it takes, difficulty of the task); (4) I was distracted by my environment (sound/temperature, etc.) or by my physical state (hungry/thirsty); (5) I was daydreaming/ I thought about task-unrelated things, (6) I was not paying attention, but I did not think about anything specific.

Consistent with other research (e.g., Stawarczyk et al., 2011), we labeled response option 3 as *task-related interference*, option 4 as *external distraction*, option 5 as *mind wandering*, and option 6 as *inattentiveness*. We labeled option 2 as *mental-elaboration*. Response option 1 was included to sample if participants were rehearsing during the blank period and was labeled as *on-task* thought in this study. We refer to all the other response options (i.e., excluding on-task) combined as *off-task*.

2.4. Procedure

When participants entered the eye-tracking room, they received instructions on the procedure of the experiment and were asked to sit down in front of the computer and eye-tracker. Following the instructions, the chin-rest was adjusted to the height of the participant and a calibration of the eye-tracker was performed. After calibration, the experiment started.

The participants were first presented with a reminder on the decision rules in the processing task (decision rules: 'Does this object fit in a shoebox' or 'Does this word describe me?') and the corresponding response mapping (press 'm' for yes and 'z' for no). After instructions, one block of 4 practice trials followed. Each trial started with an instruction on the decision rule required in the processing task and a reminder to the response mapping. This instruction remained on the screen until the participants pressed the space bar. Thereafter, a fixation cross was shown at the center of the screen for a random interval between 800 and 1200 ms. Following the fixation cross, the first storage item was presented in the matrix at a random and unique (not previously occupied within a single trial) position for 1 s. This allowed the participants to encode the stimulus. Subsequently, a 4 s self-paced processing task started with the presentation of a processing word at a random location in the same matrix. The locations of the words were random and changed every second from position to position to ensure interference with rehearsal during the processing task itself. After processing, the matrix was cleared and remained empty on the screen for 2 s. During this blank phase, participants could rehearse the items (or engage in any other cognitive activity, since there was no instruction). The storage phase, processing phase, and blank were repeated a number of times equal to the span (3 or 4). Thereafter, the trial ended with a prompt to recall the item locations in sequential order. On practice trials, feedback was presented after recall showing performance on recall and the processing task.

In this within-subject design, all participants performed both conditions with half of the trials being 'shoebox' trials (48 trials) and the other half being self-referential processing trials. The 96 trials were distributed across 6 blocks (16 per block), with an equal amount of trials for both conditions and span in each. Thought-probes were equally but randomly distributed across the experiment (48 in total, 8 per block). The order of the trials within the blocks was randomized for every participant. The practice block was similar in its structure to the experimental blocks except for the fact that it contained a total of 4 trials and these trials were only of span 3. Completing the experiment took approximately an hour.

2.5. Preprocessing eye-tracking data

To prepare the eye-tracking data for analysis, we performed several preprocessing steps. First, we removed all the automatically detected blinks from the data including 100 ms before and after the blink events. In addition, sudden downward jumps in pupil size (> 200 units in pupil size in one sample, comparable to 0.5 SD in pupil size) were regarded as artifacts and subsequently removed. The discarded data were linearly interpolated and the resulting full data set was down-sampled to 100 z.

Following down-sampling, we segmented the data into trials with only storage, processing, and blank periods (removing the inter-trial intervals). To calculate the average pupil size in the blank periods, we selected the pupil size measurements recorded during fixations, thereby leaving out saccades (see also Unsworth & Robison, 2016). Given the spatial nature of our task and the hypothesized differences in eye-movement behavior, we subsequently corrected the pupil size measurements for gaze direction with linear regression (for details about this method see Brisson et al., 2013). The linear regression model quantified the relationship between the X- and Y-coordinates of the eye gaze and the pupil size. Because the eye-tracker system recorded pupil size in arbitrary units and individual participants had different mean pupil sizes, we thereafter z-score normalized the pupil size data within participants (see also Franklin et al., 2013; Smallwood, Brown et al., 2011; Unsworth & Robison, 2016). The average pupil size for the different conditions and probe responses was then computed by averaging the z-score normalized pupil size for each individual blank

period.

As a proxy for rehearsal activity, we determined the number of correct fixations in each blank period. We corrected this for how many fixations a participant made by dividing it by the total amount of fixations counted in the blank period. Correct fixations were defined as fixations on locations where previously in a trial a storage item was presented. We checked whether any drift in the measurement of X- and Y-coordinates affected the integrity of the rehearsal activity score. Drift in the measured coordinates of the eye gaze could have led to incorrect classification of the fixations' location (with locations we refer here to the cells in the 4×4 matrix). Correcting of the coordinates for drift in the experiment with linear regression did not change the classified location of the fixations. Therefore, drift in the measurements did not affect the rehearsal activity score.

2.6. Statistical analysis

All analyses were performed on trials followed by a thought-probe (i.e., half of the data). This made sure that tests on condition and thought-probe responses were done on identical data sets. We refer to the Inline Supplementary Material Table 1 for all the test results on the full data set. Results from the full data set did not change most of the conclusions in this paper.¹

Inline Supplemental Material Table 1 can be found online at <http://dx.doi.org/10.1016/j.concog.2017.12.004>.

The main dependent variable in the behavioral analysis was memory performance on the task. We expressed memory performance as a proportion correct score, computed by dividing the number of correct responses by the span for each trial. Average pupil size and rehearsal activity (see previous section) were used as dependent variables in the eye-tracking analysis. Predictors of interest included condition (self-referential processing, control), span (3, 4), block (1–6), thought-probe response (1–6), attentional state (on-task, off-task), and response times in the processing task (in seconds).

Hypotheses in the behavioral analysis and eye-tracking analysis were tested with chi-squared likelihood ratio tests comparing an intercept model with a model containing only the factor of interest. Contrast testing was performed with Tukey Post-Hoc tests. Since memory performance and rehearsal activity were expressed as proportions, we fitted them as generalized linear mixed effect models with Laplace approximation, assuming a binomial distribution with a logit link function. Models with pupil size or response times as dependent variable were fitted as maximum likelihood linear mixed effects models.

We used the R statistical programming language (www.r-project.org, version 3.2.4) to perform all the statistics. For fitting the linear mixed effect models and generalized models we used the 'lmer' and 'glmer' function from the lme4 package (version 1.1-12).

3. Results

3.1. Behavioral results

The main goal of the behavioral data analysis was to investigate whether self-referential processing (SRP) decreased memory performance on the task. With that, we also wanted to verify whether participants reported more often to be off-task (i.e., not rehearsing the targets) in self-referential processing trials compared to control trials, and whether this difference existed because of an increase in self-generated thoughts (i.e., mental-elaboration and mind wandering).

The results showed that participants performed well on this task with a mean proportion correct score of 0.82 (SD = 0.28) or 82% correct on a trial. This score is similar to that observed in other studies adopting similar tasks (see e.g., Redick et al., 2012). Performance did not change with blocks ($\chi^2(5) = 8.028$, $p = .15$), implying that there was neither a learning effect nor a fatigue effect in our experiment. An alternative explanation could be that the two canceled each other out. Although performance was unaffected by blocks, participants did show significantly lower performance for span 4 trials ($M_{\text{diff}} = -0.04$, $SD_{\text{diff}} = 0.09$; $\beta = -0.306$, $SE = 0.078$; $\chi^2(1) = 15.714$, $p < .001$), demonstrating that a higher span was indeed more difficult.

In agreement with our previous study, we found a significant performance decline for self-referential processing compared to the control condition ($M_{\text{diff}} = -0.05$, $SD_{\text{diff}} = 0.09$; $\beta = -0.398$, $SE = 0.076$; $\chi^2(1) = 27.401$, $p < .001$; Fig. 3a). There was no interaction effect between condition and span ($\beta = -0.136$, $SE = 0.156$; $\chi^2(1) = 0.765$, $p = .38$), suggesting that the effect of condition on memory performance was similar for both spans. We also did not find an interaction between condition and attentional state (i.e., on-task or off-task thinking) on memory performance ($\beta = 0.232$, $SE = 0.169$; $\chi^2(1) = 1.870$, $p = .17$; Fig. 3b). This was expected, because rehearsal or the absence of it should have similar effects on memory performance in both conditions. When we tested for main effects of condition and attentional state (i.e., in one model) in the absence of this interaction, we found that being off-task significantly attenuated performance on top of what could be explained by condition ($\beta = -1.021$, $SE = 0.090$; $\chi^2(1) = 135.44$, $p < .001$). As Fig. 3b clearly shows, the impact of off-task thinking on memory performance ($\beta = -1.134$, $SE = 0.123$) was much greater compared to that of condition. Nonetheless, condition also predicted memory performance ($\chi^2(1) = 7.679$, $p = .005$), but the size of the effect was reduced with the added effect of attentional state (from $\beta = -0.398$, $SE = 0.076$; to $\beta = -0.219$, $SE = 0.079$). This shows that condition and attentional state both explain unique variance in memory performance on the task, but also that a part of the effect of condition is explained by differences in on- and off-task thinking (see Fig. 4).

Necessary to note is that in our previous study, we found that response times to the processing words (i.e., time to make each decision) were higher in self-referential processing trials and that increasing response time negatively affected memory performance.

¹ The results were the same as on half of the data set, except for the effect of condition on pupil size. Condition was significant in the full data set, but not in the reduced data set. However, since the effect size was small in both data sets, we conclude that the true effect of condition on pupil size was only marginal.

Fig. 3. Mean proportion correct separated by span and condition (A) and separated by attentional state and condition (B). SRP = self-referential processing, control = shoebox. On-task = reports of rehearsal of the targets, off-task = reports of thoughts not related to rehearsal. Error bars represent one standard error of the mean.

Fig. 4. Overview of the mean frequency of different thought-probe categories in the self-referential processing (SRP) and control condition (A) and memory performance as mean proportion correct for each thought-probe category (B). Error bars represent one standard error of the mean.

Similar results were found in the present study. With increasing response times we found a decrease in performance on the task ($\beta = -0.930$, $SE = 0.164$; $\chi^2(1) = 31.57$, $p < .001$). The average response time for the semantic processing decisions (e.g., ‘Does marble fit in a shoebox?’) in the control condition was 99.2 s ($SD = 23.5$ s), whereas the self-referential processing decisions (e.g., ‘Am I kind?’) took on average 115.9 s ($SD = 30.7$ s). This difference in response time was found to be significant ($\beta = -0.167$, $SE = 0.010$; $\chi^2(1) = 249.42$, $p < .001$). These results indicate that the increase in response time in the self-referential processing condition was not used to rehearse the targets, otherwise an improvement in memory performance would be expected.

A possible explanation for the longer response times with self-referential processing, is that the processing was more cognitively demanding compared to the semantic processing in the control condition. Therefore, an alternative explanation for the observed performance decrement is that higher cognitive demand (i.e., task difficulty) when performing self-referential processing, reflected in longer response times, caused the lower memory performance. We reanalyzed the effect of condition on memory performance with an added fixed effect for the response times in the processing task. This allowed us to test whether there was an effect of condition while assuming that response times were constant. We found that self-referential processing still predicted lower memory performance when we controlled for response times ($\beta = -0.268$, $SE = 0.083$; $\chi^2(1) = 10.265$, $p = .001$), but the effect did become smaller (from $\beta = -0.398$ to $\beta = -0.268$). When we also added attentional state to the model, condition was not significant anymore ($\beta = -0.112$, $SE = 0.086$; $\chi^2(1) = 1.668$, $p = .19$), but we did find an effect for attentional state ($\beta = -1.007$, $SE = 0.090$; $\chi^2(1) = 130.41$, $p < .001$) and a relatively smaller effect for response times ($\beta = -0.571$, $SE = 0.184$; $\chi^2(1) = 9.402$, $p = .002$). Taken together, these results show that the observed performance decrement can most likely be explained by differences in how often the participants were not rehearsing the targets (i.e., off-task), and in part by the higher difficulty of the self-referential processing task.

3.1.1. Thought-probe results

Analyzing the distribution of thought-probe responses revealed that participants were off-task in 51.0% of the trials (see Fig. 4). This means that participants reported having other thoughts than rehearsal of the targets on half of the analyzed trials. The proportion of off-task reports was higher in the self-referential processing condition ($\chi^2(5) = 87.379$, $p < .001$), with 60.2% off-task in self-referential processing trials and 41.8% in control trials. Most importantly, post hoc testing showed that participants experienced more self-generated thought with more *mind wandering* ($\beta = 0.938$, $SE = 0.214$; $z = 4.381$, $p_{\text{adjusted}} < 0.001$) and more *mental-elaboration* ($\beta = 1.164$, $SE = 0.138$; $z = 8.441$, $p_{\text{adjusted}} < 0.001$) when processing self-referential material. We found that in the self-referential processing condition the number of mental-elaboration reports doubled (from $M = 14.1$ –30.7%), and that mind wandering nearly doubled (from $M = 5.1$ –8.9%) in comparison with the control condition. Having off-task thoughts during a trial was found to negatively impact task performance ($\chi^2(5) = 122.71$, $p < .001$) and similar post hoc testing showed that all different thought-probe reports were associated with lower performance on the task (all $p_{\text{adjusted}} < 0.001$).

Similar to the previous section, where we analyzed the effect of condition under simultaneous statistical control for attentional state and response times, we found that the different thought-probe reports ($\chi^2(5) = 172.53$, $p < .001$) and response times ($\beta = -0.582$, $SE = 0.185$; $\chi^2(1) = 9.647$, $p = .002$) reliably affected memory performance but not condition ($\beta = -0.102$, $SE = 0.088$; $\chi^2(1) = 1.668$, $p = .24$). Interestingly, post hoc testing revealed that both *mental-elaboration* ($\beta = -0.840$, $SE = 0.109$; $z = -7.734$, $p_{\text{adjusted}} < 0.001$) and *mind wandering* ($\beta = -1.447$, $SE = 0.153$; $z = -9.485$, $p_{\text{adjusted}} < 0.001$) and the other reports (all $p_{\text{adjusted}} < 0.001$) significantly decreased performance. Taken together, the results show that self-referential processing increased the frequency of self-generated thought (i.e., mental-elaboration and mind wandering) and that the occurrence of self-generated thought was detrimental to performance on the task.

3.2. Eye-tracking results

The aim of the eye-tracking data analysis was twofold. First of all, we wanted to objectively determine whether there was less rehearsal activity in self-referential processing trials, in trials reported as off-task in general, and specifically in trials with self-generated thought. If so, this would provide support for our model mechanism claiming that rehearsal is more often replaced by another process (presumably self-generated thought) in the self-referential processing condition. Furthermore, we wanted to examine the influence of condition and different thought-probe reports on the average pupil size, which is thought to be smaller for self-referential processing and – across both conditions – for trials with mind wandering.

3.2.1. Eye-movement – rehearsal

Our analysis showed an average rehearsal activity of 0.48, meaning that on average 48% of the fixations during blank periods were on locations where previously a target was presented. This is substantially more than would be expected by chance if eye-movements were unrelated to rehearsal and therefore random. In that case the rehearsal activity would be 0.12, which is the average probability of accidentally looking at a target location combined for span 3 and span 4 trials. The average rehearsal activity performed by the participants varied substantially ($SD = 0.37$), with averages as high as 0.67 and as low as 0.29. The correlation between rehearsal activity and memory performance on the task was small ($r = 0.36$, $df = 30$, $p = .045$) and also showed substantial variation (95% CI [0.01, 0.63]). The variability in average rehearsal activity and in its relationship with memory performance reflects that not all participants used and/or benefited as much from eye-movements to perform rehearsal.

Consistent with our prediction that self-referential processing would interfere with rehearsal, we found a difference between conditions in rehearsal activity ($\beta = -0.076$, $SE = 0.027$; $\chi^2(1) = 8.174$, $p = .004$). This difference was however very small with an average difference of 2% in correct fixations ($SD_{\text{diff}} = 7\%$). Together with the weak correlation ($r = 0.36$) between memory

Fig. 5. Overview of rehearsal activity during blank periods for on-task vs. off-task trials (A; all thought-probe responses combined except for on-task) and the entire distribution of thought-probe responses (B). Error bars represent one standard error of the mean.

performance and rehearsal activity, this suggests that variation in (overt) rehearsal may not explain why we see a decrement in memory performance between the conditions.

However as we have seen in the previous paragraph, not all participants relied on overt rehearsal. Therefore, we also analyzed the effect of condition on rehearsal activity while taking individual differences in the relationship between rehearsal activity and memory performance into account. We computed a correlation coefficient between each individuals' rehearsal activity and their memory performance to obtain a measure of 'reliance' on eye-movements to memorize the targets for each participant. We tested for an interaction between condition and reliance on eye-movements for rehearsal, and found that rehearsal activity decreased in self-referential processing trials with increasing reliance ($\beta = -0.493$, $SE = 0.153$; $\chi^2(1) = 10.315$, $p = .001$). In other words, participants that used overt rehearsal and benefited from using it showed a stronger decrease in rehearsal in self-referential processing trials.

Alongside differences between conditions, we were also interested in the effects of self-generated thought and other off-task thought on rehearsal activity. We predicted that when participants reported to have other thoughts than rehearsing the targets (i.e., off-task), we would find a decrease in rehearsal activity measured in eye-movement. Our results confirmed this prediction ($\beta = -0.154$, $SE = 0.029$; $\chi^2(1) = 28.349$, $p < .001$; see Fig. 5). The effect of attentional state was not found to significantly differ between conditions ($\beta = -0.042$, $SE = 0.056$; $\chi^2(1) = 0.566$, $p = .45$).

Analyzing the individual thought-probe responses in more detail, we found that all the responses collectively impacted rehearsal activity ($\chi^2(5) = 37.742$, $p < .001$). Post hoc testing revealed that only *mind wandering* ($\beta = -0.221$, $SE = 0.058$; $z = -3.789$, $p_{adjusted} = 0.002$), *mental-elaboration* ($\beta = -0.185$, $SE = 0.036$; $z = -5.203$, $p_{adjusted} < 0.001$), and *inattentiveness* ($\beta = -0.215$, $SE = 0.009$; $z = -2.896$, $p_{adjusted} = 0.04$) were associated with less rehearsal activity. Therefore, not all off-task thinking impacted rehearsal activity equally. As can be seen from Fig. 5b, trials with task-related interfering thoughts had very similar rehearsal activity scores. Trials where participants experienced external distraction showed a lower but also more variable average rehearsal activity.

Since the response times in the processing task were found to differ between conditions and to affect memory performance, we also analyzed the influence of these response times on rehearsal activity. We expected to observe less rehearsal when more effort is put in processing of the word stimuli. Our results confirmed that indeed longer response times predicted less rehearsal activity ($\beta = -0.215$, $SE = 0.036$; $\chi^2(1) = 36.819$, $p < .001$). Under simultaneous statistical control of individual thought-probe reports (results were similar for attentional state) and response times, we found no evidence anymore for an effect of condition on rehearsal activity ($\beta = -0.002$, $SE = 0.028$; $\chi^2(1) = 0.006$, $p = .94$). However, individual thought-probe reports ($\chi^2(1) = 27.839$, $p < .001$) and response times ($\beta = -0.194$, $SE = 0.037$; $\chi^2(1) = 28.006$, $p < .001$) did significantly impact how much rehearsal activity was present in the blank periods. Post-hoc testing showed that only the self-generated thought states *mental-elaboration* ($\beta = -0.161$, $SE = 0.034$; $z = -4.367$, $p_{adjusted} < 0.001$) and *mind wandering* ($\beta = -0.205$, $SE = 0.056$; $z = -4.367$, $p_{adjusted} < 0.001$) reliably influenced rehearsal. Taken together, we conclude that the observed difference in rehearsal activity between the conditions is likely explained by an increase in self-generated thought and by increased difficulty of processing in the processing task.

3.2.2. Effects of the task on pupil size

Prior to analyzing the average pupil size, we first wanted to examine the dynamics of the pupil size within a trial. Since little is known about pupil size over the course of a complex working memory task, we first examined pupil size over the whole task (Fig. 6). As can be seen from the figure, the individual phases (i.e., storage 'S', processing 'P', and blank 'B') are easily distinguishable. The processing phases yielded the largest pupil size, followed by the storage phase and the blank phase. As the relative size of the pupil is known to be positively correlated with mental effort (see e.g., Beatty, 1982), this could mean that the processing task required most effort. This ordering in the phases is to be expected, as the storage phase only involved memorizing one extra target, and the blank phase did not require anything except for optional rehearsal.

In this study we focused our hypotheses on the blank phases, therefore we calculated the average pupil size in these parts of the

Fig. 6. Mean pupil size in a single span four trial. S = storage phase (i.e. presentation of new target item), P = processing phase, B = blank phase.

trial. Unlike many other mind wandering studies where the average is calculated from a relatively steady pupil size, our period shows a substantial decrease in the size of the pupil from its onset (Fig. 6). This decline attenuated as the trial progressed, suggesting that magnified storage load also relatively increased exerted mental effort. Despite the observed decline, we believe that this does not affect the validity of our average pupil size measures. As can be seen in Fig. 7b, the difference in the average pupil size is very similar throughout the blank phase. Furthermore, the difference in average pupil size was found to not differ between phases across condition ($\chi^2(3) = 0.997$, $p = .80$), across different thought-probe responses ($\chi^2(3) = 16.439$, $p = .36$) and attentional state ($\chi^2(3) = 2.513$, $p = .47$).

3.2.3. Average pupil size in blank periods

After analyzing the task dynamic effects of the task on the pupil size, we first examined the relationship between the average pupil size during blank periods as an indicator of alertness/arousal and condition (Fig. 7a and b). We expected to find a smaller average pupil size for the self-referential processing condition due to increased mind wandering. As can be seen in Fig. 7, the average pupil size behaved in the hypothesized way with a relatively smaller pupil size during blank periods in self-referential processing trials. However, this difference was not significant ($\beta = -0.039$, $SE = 0.023$; $\chi^2(1) = 2.500$, $p = .11$).

The manipulation did not significantly affect the average pupil size in blank periods, but how did the pupil react to off-task thinking? Our analysis showed that the average pupil size was lower in off-task trials compared to on-task trials ($\beta = -0.089$, $SE = 0.024$; $\chi^2(1) = 13.363$, $p < .001$), suggesting a lower state of alertness and arousal when participants reported not to rehearse the targets (Fig. 8a). Similar to rehearsal activity, we found no evidence for an interaction effect between condition and attentional state on the average pupil size ($\beta = 0.051$, $SE = 0.050$; $\chi^2 = 1.059$, $p = .30$).

We also analyzed the distinct influences of different off-task reports on the average pupil size. Confirming our prediction in line with Unsworth's study, we found that *mind wandering* was associated with a smaller average pupil size ($\beta = -0.266$, $SE = 0.049$; $z = -5.406$, $p_{\text{adjusted}} < 0.001$). In addition, a similar effect was found for a state of *inattentiveness* with no specific recollection of thought ($\beta = -0.337$, $SE = 0.063$; $z = -5.338$, $p_{\text{adjusted}} < 0.001$). In contrast to Unsworth, the average pupil size for *external distraction* was smaller instead of larger ($\beta = -0.251$, $SE = 0.052$; $z = -4.830$, $p_{\text{adjusted}} < 0.001$). This difference can potentially be explained by the nature of our task. Our task was much more visually demanding than the sustained attention task in Unsworth's

Fig. 7. Overview of the average pupil size during the blank phase by condition (A) and across time by condition (B). Error bars represent one standard error of the mean.

Fig. 8. Overview of the average pupil size during the blank phase by on-task vs. off-task (A) and across separate thought-probe categories (B). Error bars represent one standard error of the mean.

study, and given that the pupil responds to both arousal and mental effort, one potential explanation is that a distraction from the task resulted in lower arousal and therefore a smaller average pupil size. From both we can expect a lower arousal state and hence a smaller pupil size. For both *mental-elaboration* ($\beta = 0.046$, $SE = 0.031$; $z = 1.503$, $p_{\text{adjusted}} = 0.64$) and *task-related interference* ($\beta = -0.077$, $SE = 0.039$; $z = -1.951$, $p_{\text{adjusted}} = 0.35$) we found no significant difference in pupil size with on-task.

Longer response times during the processing task were found to increase the average pupil size in the blank periods ($\beta = 0.233$, $SE = 0.029$; $\chi^2(1) = 58.985$, $p < .001$). Since larger pupil sizes are commonly associated with increased mental effort or resource allocation, this supports the idea that the self-referential processing was more cognitively demanding compared to the semantic processing in the control condition. Controlling for response times by adding it as a fixed effect in our linear mixed effects models did not change any of the preceding conclusions.

4. Discussion

In agreement with earlier work (viz., Daamen et al., 2016), we showed that performance on a spatial complex working memory task was worse when participants had to perform self-referential processing compared to semantic decision-making (i.e., control condition). This consistency between studies with different stimulus sets indicates that the observed performance decline is robust and reliable. Our results suggested that there were two main factors that contributed to the observed performance decline: distracting processes (such as self-generated thought) that interfered with memorizing the targets, and increased cognitive demand for the self-referential processing task.

From the thought-probe reports, we observed that participants reported less rehearsal of the targets in blank periods following self-referential processing (49.8% vs. 58.2% for control). Instead we found higher incidences of self-generated thought, with twice as many reports of mental-elaboration on the processing material (14.1–30.7%), as well as an increase in mind wandering (5.1–8.9%). The increase of self-generated thought provides confidence in our cognitive model, which assumes that self-related material can increase the likelihood of processes that issue elaborative thought, and that such processes can be initiated at spare moments in the task.

Increased reports of mental-elaboration with self-referential processing are in line with existing theories about self-reference in autobiographical memory (Barnhofer et al., 2007; Conway & Pleydell-Pearce, 2000; Conway, Singer, & Tagini, 2004; Wessel et al., 2014). According to Conway et al. (2004), the main function of autobiographical memory is to provide an accurate window on our current personal goals and values such that we can behave in a goal driven manner. With that, we try to maintain a sense of self that is consistent with these goals and values (called ‘self-coherence’). When participants processed self-referential material in our experiment, the stimuli might have given rise to thoughts about events that conflicted with their sense of self. Conway and colleagues suggested that this self-discrepancy automatically triggers elaborative thought to resolve this conflict, distracting us from our initial memory search. The mental-elaboration that we observed in our study might therefore reflect an effort of participants to resolve discrepancies of the self with their current goals and values. Interestingly, mental-elaborations in our study occurred outside of the context of the processing task, therefore drawing attention away from the task to memorize the targets in favor of self-generated thinking. Our study therefore suggests that mental elaborations can be pervasive.

It is interesting that also mind wandering occurred more often in trials involving self-referential processing. We hypothesized that processing self-related material would increase the amount of mind wandering, because it might trigger associations in memory with e.g. concerns that are unrelated to the task. The increase in our study provides some support for this hypothesis. Still, reports of mind wandering were infrequent (5.1% for control, 8.9% for self-referential processing). Although the amount of mind wandering did almost double from the control condition, we do think that given the small amounts of observed mind wandering, more research is warranted before we can conclude that self-referential processing is a good manipulation for mind wandering.

Alongside thought-probe reports, we also examined participants' eye-fixations and pupil size to obtain a more fine-grained picture on how self-referential processing and self-generated thought influenced cognitive processes during the blank periods. Eye-fixations were used to determine overt rehearsal activity by computing what percentage of eye-fixations were on locations where previously in a trial a target was presented. Our results showed that such fixations occurred much more often than chance (48% instead of 12%) and that rehearsal activity measured in this way was positively correlated with memory performance ($r = 0.36$). At the same time, the limited magnitude of the correlation indicates that not all participants needed eye-fixations to memorize the targets. Consequently, we argue that our measure did reflect overt rehearsal, but that it could not capture all rehearsal activity. In particular rehearsal from covert memorization strategies (i.e., without eye-movements) were likely not reflected in the measure (see also Godijn & Theeuwes, 2012).

Consistent with this proposal, we also observed less overt rehearsal in blank periods of trials where participants experienced self-generated thought. This suggests that self-generated thought could interfere with rehearsal in the spare moments of the task, providing some support for our model assumption that self-generated thought replaces rehearsal processes. We furthermore expected to find a similar reduction in rehearsal activity in self-referential processing trials because of self-generated thought. Our results indeed indicated a reduction, but the size of this effect was very small ($M = -2\%$ in rehearsal). Considering that not all participants relied as much on overt rehearsal to memorize the targets we did find a stronger effect for participants that benefited more from overt rehearsal. For that reason, we argue that self-referential processing indeed could interfere with rehearsal in the blank periods of the trial. For participants that relied on overt rehearsal, this likely also attenuated performance.

Our pupil size results showed that different manifestations of self-generated thought were differentially associated with the size of the pupil. In agreement with many earlier studies using cognitively undemanding task (see e.g., Grandchamp et al., 2014; Mittner et al., 2014; Unsworth & Robison, 2016), our results indicated that mind wandering was associated with a smaller pupil size. A smaller pupil size as correlate for mind wandering may therefore also generalize to demanding paradigms. The smaller pupil size during blank periods reflected that mind wandering occurred in a state of lower arousal and alertness, providing additional support for our model prediction that self-generated thinking disrupted task-focus during spare moments. Unlike mind wandering, mental-elaborations were not found to be associated with a different pupil size in comparison with efforts to rehearse the targets (i.e., on-task thought). Conway and Pleydell-Pearce (2000) argued that mental-elaboration involves strategic retrieval processes that require control processes. Therefore, this potentially suggests that mental-elaboration required similar amounts of control processes compared to efforts to memorize the targets, resulting in a similar average pupil size.

It should be noted that next to self-generated thought also cognitive demand of the processing task was an influential factor. Self-referential processing appeared to be more demanding, with higher average response times compared to control. Higher response times negatively impacted memory performance and rehearsal activity, and increased pupil size. Therefore all the results are at least in part explained by the fact that the self-referential processing task was more difficult to perform. Nonetheless, all our analyses indicated that even after controlling for response time, an effect of self-generated thought remained, suggesting that cognitive demand in the self-referential processing condition is not the only factor causing differences in memory performance.

To summarize, the results and discussions above suggest that processing self-related material could increase the amount of self-generated thoughts in the task at moments when they prevent memory rehearsal. The negative impact of such lingering thoughts on memory performance, attenuation in pupil size (only for mind wandering), and reduction in goal-driven eye-movement behavior in spare moments of the task, likely indicates that self-generated thought interfered with the task goal to memorize the targets. This study therefore provided some support for our computational cognitive model assuming that distracting self-generated thought occurs as a result from competition between processes of the task (i.e., rehearsal) and processes that cause self-generated thoughts. In addition, we found support that self-referential processing can leverage the competition towards self-generated thought.

4.1. New insights on self-generated thought in demanding tasks

With increased confidence that self-referential processing could increase self-generated thought, and that self-generated thought could interfere with memorizing the targets, we think it is important to discuss what this study can tell us about self-generated thought in demanding contexts.

First of all, this study indicates that self-generated thought is not restricted to undemanding tasks, but that it is also pervasive in demanding contexts, even when engaging in it is irrelevant to performance on the task. Based on our cognitive model and existing research, we believe that the occurrence of such thought depends on two important factors. First of all there needs to be an *opportunity for self-generated thought* to start i.e., there should be no ongoing task processes that prevent off-task thinking from occurring. In other words, the necessary cognitive resources for self-generated thought need to be available. This is in line with resource theories of mind wandering, which claim that mind wandering is a process that requires resources to start and to continue (see e.g., Levinson, Smallwood, & Davidson, 2012; Smallwood & Schooler, 2006). In addition, it is consistent with existing multitasking theories, in particular that of threaded cognition (Salvucci & Taatgen, 2008, 2010). Threaded cognition assumes that cognition involves multiple cognitive resources (e.g., vision, control, motor, retrieval) and that various tasks in a multitasking setting require different or similar resources at a given time. When tasks ask for different resources, they can be carried out in parallel. This account predicts that people switch tasks when the resources for another task are available. That this happens was shown by a recent task-switching study of Katidioti and Taatgen (2014), who observed that participants switched between the main task and an interrupting secondary task when faced with a short delay in the main task (i.e., forced delay of 3 s). The delay periods in their study parallel with the blank periods in the present experiment. Therefore, this would predict that the blanks provided an opportune moment in our task to switch to thinking such as elaborative thoughts or mind wandering. The results of this study indicated that self-generated thinking in general

indeed existed in the blank periods, and given that blanks were frequent, this can explain why self-generated thought could occur frequently in our CWM task despite the fact that cognitive demands were high.

The second important component is that processes leading to self-generated thought have to *compete with task processes* when opportune moments occur. This competition involves selecting either task related processes or self-generated thought processes, and can be influenced by the relative priority of such processes at a given time. On the surface, this idea is consistent with the control failure theory of mind wandering (McVay & Kane, 2009), which explains that mind wandering occurs when we fail to maintain task focus. Our model, however, does not require any control processes to explain this, as the selection process is fully automatic. When resources for mind wandering are available, processes from different tasks and goals will compete. The relative priority of these processes will determine what will be thought about next. The results of our study suggested that self-referential processing may be such a strongly competitive process.

4.2. Implications for aptitude measurement

The results of this study could have implications for measuring working memory capacity in aptitude assessment. In research, but also in many applications outside of research, we measure working memory capacity and similar aptitudes to predict someone's success in various situations (Conway et al., 2005). Why working memory capacity has predictive utility in many different contexts is unknown, however the present study suggests that the ability to maintain task-focus is an important factor (see e.g., Kane, Hambrick, & Conway, 2005). We found that self-generated thought and other distractions significantly impacted working memory performance, therefore failures to maintain task focus were an important predictor of performance. Similar results were found in a recent study of Mrazek et al. (2012). The researchers determined that mind wandering behavior explained 49% of the variation in performance on a working memory test, general intelligence test, and a scholastic aptitude test.

From the above we could conclude that the ability to maintain focus on our current activities is likely an important component of aptitude tests. Although this may be an important ability, we believe that caution is needed. In our study, we were able to manipulate the prevalence of self-generated thought and therefore the measured working memory performance. This shows that context can have a substantial influence on measuring working memory capacity. When people have for example pressing concerns or experience conflicts with their sense of self, this could increase self-generated thought and that could in turn decrease the measured working memory capacity (see Klinger & Cox, 2004). We therefore believe that it is important to keep these effects in mind when interpreting the results of working memory assessments and other aptitude tests.

5. Conclusions

In this study we aimed to give more insight in how and why we engage in self-generated thought in a cognitively demanding task, and how self-referential processing influences self-generated thinking. The results of this study and the model of the task suggested that distracting self-generative thoughts in demanding tasks can be pervasive and that they might arise when cognitive resources are available, such as when there are natural breaks in current ongoing activities. How likely and how often self-generated thought occurs potentially depended on the relative priority of the current task to other goals that compete for attention. Processing self-related information could bias the priority of self-generated thought, but one could also think that other processes such as boredom or fatigue can affect the relative priority of the current task goal and other goals. Therefore, in order to explain internally-directed behavior in demanding tasks, one has to consider both how natural task breaks and the availability of resources can allow it to arise, and how likely one can maintain task focus in such situations.

Author note

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at <http://dx.doi.org/10.1016/j.concog.2017.12.004>.

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