Measuring and modeling distraction by self-referential processing in a complex working memory span task

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Abstract

Two experiments using novel complex working memory span tasks were performed, both requiring the participants to remember a span of letters whilst being distracted by the processing of words. Word processing could either be self-referential (SRP) or not. In the first experiment recall performance was compared between SRP and non-SRP conditions using the same words. In the second experiment, we compared SRP and non-SRP in two tasks equalized in semantic processing but using different words. In both experiments recall performance was significantly lower after SRP compared to non-SRP, indicating that SRP has a disruptive effect on the recall task. A cognitive model implemented in PRIMs, using goal competition during SRP, interfering with rehearsal of letters, could account for the observed experimental results. If SRP interferes with subsequent tasks in this manner it should also interfere with tasks other than recall, such as SRP occurring in daily life.

Keywords: self-referential processing, distraction, cognitive modeling, complex working memory

Introduction

Distractions from ongoing tasks form a problem in our day-to-day lives, it reduces our productiveness and can have negative consequences on task performance. Distractions can come from our perceptual inputs (external) or from our mind (internal), the latter can be viewed as distractions by self-generated thought, that is "*mental contents that are not derived directly from immediate perceptual input*" (Smallwood & Schooler, 2015). These thoughts can occur as part of a task, for example when one needs to construct an internal representation or mentally weigh the different factors of a decision, or they can be task independent when they stray from the task at hand, for example when we let our minds wander. In demanding tasks such as driving a car or piloting a plane the consequences of internal distractions can be severe (Casner & Schooler, 2014; Yanko & Spalek, 2013 respectively).

Having objective measures of distractions caused by self-generated thought and having a better understanding of the mental processes underlying them will allow us to better understand and prevent undesired effects of mental distraction during important tasks. For this reason we set out to measure and model the distractions caused by self-generated thought during self-referential processing (SRP), the processing of information in relation to the self (see introduction Northoff et al., 2006). We therefore designed a novel experimental paradigm to measure the distracting effects SRP on one's ability to recall presented letters, using a complex working memory (CWM) span task as a basis. We hypothesized that distraction by SRP leads to worse CWM span task performance than distraction by a non-SRP task as SRP may lead to task-unrelated self-generated thoughts instead of task-related maintenance rehearsal.

Methods

Two CWM span task experiments were performed varying only slightly in set-up. The first experiment will be described in detail, for the second experiment only the differences with the first will be noted.

Experiment 1

Participants

Subject recruitment for both experiments was done via a Facebook post on the "*Paid research participants Groningen*" group offering 10 euros for those who decided to participate (experiment duration approximately 1 hour). 27 participants were included in the first experiment (19 female, age 22.3 ± 2.7). Only native Dutch speakers were included in the experiment. Informed consent was obtained from all participants.

Task

In this experiment participants were required to remember presented letters while processing presented words (Figure 1). It was created using PsychoPy (Peirce, 2007).

The screen background was dark grey and all text was presented in white (Gill Sans MT, font height ~1cm). The experiment consisted of 12 blocks, with one block containing each combination of span and condition once. The spans used were 3, 4 and 5, as is common in CWM span tasks (Conway et al., 2005). For the storage task, participants needed to remember letters that were presented one at a time on the screen for 1s, and between each presentation there was 4s of self-paced processing of word stimuli (SRP or neutral – see below). Before each letter presentation the screen was blank for 1s to allow for rehearsal. We included these delays on purpose to maximize the potential for distraction by SRP.

Each trial started with showing the participant the current condition. For the SRP condition this was "Does this word describe you? (Yes/No)", for the neutral condition this was "Does the word contain the letter 'a'? (Yes/No)". The letter 'a' was chosen for the neutral condition because it was present in roughly half of the used word stimuli (48.0%). Both sentences were in Dutch. Participants were able to respond by pressing the left (labeled 'NO') or right 'ctrl' (labeled 'YES') buttons.

In the next phase a random letter stimuli was presented in the center of the screen for 1.0s. Before the presentation the screen was blank for 1.0s. Directly after the letter presentation followed 4.0s of self-paced processing tasks (SRP or non-SRP). As soon as a participant responded to a word the next word would be presented. If there were less than 700ms remaining, the screen would stay blank for the remaining time to prevent participants being flashed by a stimulus at the end of the phase. These phases were repeated a number of times equal to the current span.

The recall phase was indicated by a number of underscores equal to the current span. The underscores were replaced by the user's input as they started typing. Error correction was possible by using the backspace key. When they entered the last letter the feedback was presented. Participants were instructed to guess if they couldn't remember a letter. The participants were shown how well they did on the storage task 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 neutral condition. Due to the subjectivity of the SRP condition there was no score shown. A pilot study showed that participants were consistent with their previous responses in the SRP condition, indicating that feedback on this was not critical.

Scoring

The storage task 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. The processing task was scored using the percentage of correctly processed items. If the last processing item did not receive a response before going to the next phase, this item wasn't taken into account for the final score.

Stimuli

To-be-remembered stimuli were chosen 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. No vowels were used to prevent easy grouping of letter stimuli by remembering them as words. The used 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). These words were translated into Dutch.

Experiment 2

Experiment 2 differed from Experiment 1 in one key aspect, namely the non-SRP condition.

Participants

30 native Dutch participants (18 female, age 22.4 ± 4.0) were included for the second experiment. Participants from the first experiment were excluded. Written consent was obtained from all participants.

Non-SRP condition

A potential objection to the non-SRP processing task in Experiment 1 is that it does not involve semantic processing of the presented word. For that reason, we repeated the experiment with a non-SRP condition in which participants answered the question "Does this object fit in a shoebox?". Another advantage of this task is that there is no confusion possible between conditions as different word stimuli are used for the SRP and non-SRP conditions. For the "shoebox task", we used translated nouns from the Toronto Word Pool (Friendly, Franklin, Hoffman, & Rubin, 1982). 50 words were selected to which the answer was an unambiguous yes, and another 50 to which the answer was an unambiguous no.

Data analysis

The data of the experiments were analyzed using R (R Core Team, 2015). Participants with 5% of response times < 200ms were excluded from the analysis as well as participants with a mean neutral condition processing score over all trials < 85% as this would indicate that the subject was not performing the tasks. The response inconsistency for the SRP condition was also evaluated; if a participant was equally likely to respond yes or no over multiple repetitions of the same word, this would indicate that he is not performing the required task. Yes responses were scored 1 and no responses -1, their inconsistency for a given stimuli was then calculated as the variance over their responses. This results in a value of 0 when all responses are the same and 1 when there are as many yes as no responses. Participants with mean inconsistency over all word stimuli > 0.5 were excluded.

This resulted in two exclusions for experiment 1, one scored at chance in the neutral processing phase and one had

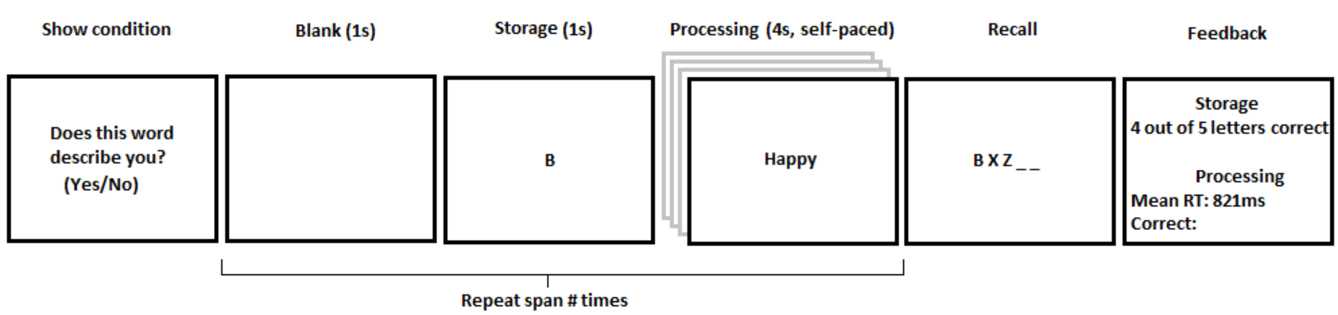

Figure 1: Overview of a single trial (SRP condition, span 5).

unrealistic low response times in the SRP condition. For experiment 2 two participants were excluded from the data analysis because they scored below 85% in the processing phase in the neutral condition.

Results

To analyze the effect of distraction by SRP we looked at the average recall score each participant attained per condition for each span. A difference in score between the SRP and natural condition indicates that one of type of distraction has a larger effect on recall than the other.

Figure 2 shows the mean score per condition per span, including 95% confidence interval bars. For all spans the average score for the SRP condition was lower than the neutral condition. To analyze this effect we performed a logistic mixed effects analysis in R (LME, Bates, Maechler, Bolker, & Walker, 2014) of the relation between condition and partial-credit score. The span and condition were entered as fixed effects and the intercepts for each participant as random effect. The reported p-values result from an ANOVA between the complete model and the model without the effect of condition. Using this approach we found that the score for the SRP condition was significantly lower than for the neutral condition ($\chi 2(1) = 6.45$, $p = 0.011$). However, after including average response time for each trial to the previous model we no longer found a significant effect of condition on score ($\chi 2(1) = 0.77$, $p = 0.38$). This means that the difference between the conditions can also be explained by a difference in difficulty of the processing task.

To examine whether the observed difference between the SRP and non-SRP was an artifact of the non-semantic nature of the non-SRP task, we conducted experiment 2, in which we replaced syntactic with semantic judgments. We again found that the score for the SRP condition was significantly lower than for the neutral condition ($\chi 2$ $(1) = 27.5$, $p < 0.001$; figure 2). After including the average response time per trial in the model there was still a significant effect of condition on score ($\chi 2$ $(1) = 6.68$, $p = 0.0097$). Therefore, in experiment 2 the difference in accuracy cannot be explained by the difficulty of the processing task.

Model

The results of experiment 2 have been modeled using the primitive elements model of skill (PRIMs; Taatgen, 2013), which has previously been successful in modeling visual distraction (Taatgen, Katidioti, Borst, & van Vugt, 2015). The key component of our distraction model is the idea that the current goals of the model activate mental operators to achieve that goal. However, the task-related operators have to compete with operators that are not activated by the goal, but by other influences. These influences can be external (e.g., a distracting visual stimulus), or internal (e.g., a task-relevant memory trace that has an unexpected association with a distracting train of thoughts). Experiment 2 was chosen as a target for modeling because it had the clearest results and didn't allow the participant to be confused between the SRP and neutral conditions (since each condition used a clearly different set of words).

Design and key elements

The model of this task requires several distinct components. It needs to store sequential information, which are the presented letters and their order. In addition to that it needs the ability to rehearse and the ability to report this information. Finally it needs to be able to process and respond to presented words, the exact mechanism of which will need to differ for the SRP and neutral condition. We will discuss these components in detail one by one.

The way we store sequential information is still unclear, there is evidence that we can chunk multiple items, treating them as one, and store positional information about each item within that chunk (Dehaene, Meyniel, Wacongne,

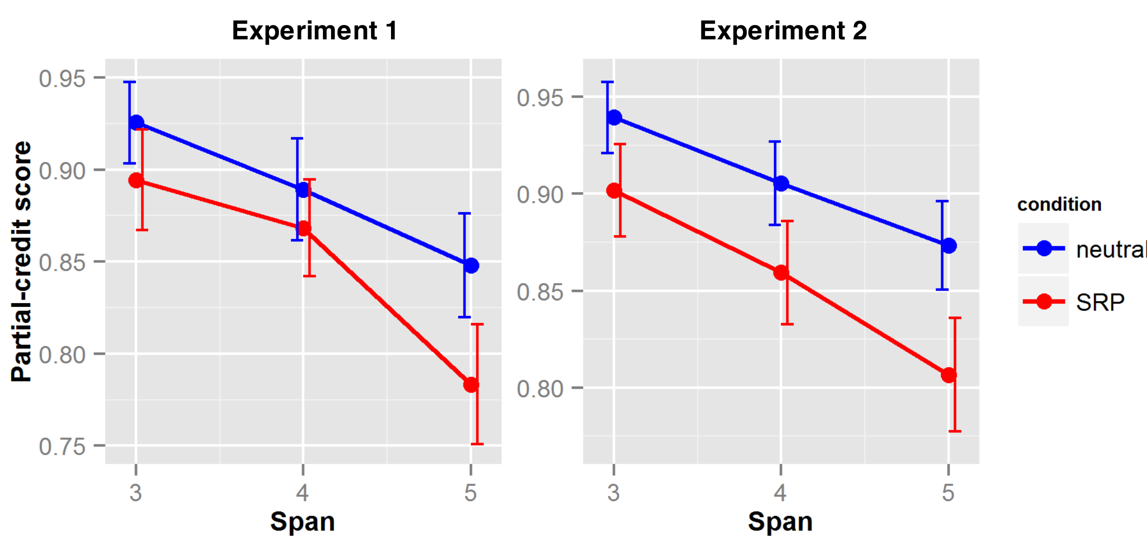

Figure 2: Recall accuracy as a function of span, comparing SRP and non-SRP (neutral) conditions. Data are shown for experiment 1 (left) and 2 (right), showing 95% confidence intervals.

Wang, & Pallier, 2015; Ladd & Woodworth, 1911). We modeled this by having position-specific operators. That is, there are separate operators for storing and retrieving each individual serial position of a letter. When storing, a chunk is created that contains positional information about an item, the item itself and a reference to the current goal chunk. The positional information and the reference to the current goal chunk is later used to try to retrieve the chunk by the position-specific operators. This reference is needed because otherwise chunks from previous trials will be recalled. If it is not successfully retrieved the model moves on to the next operator, which tries to retrieve the chunk containing the next position.

In the design of the experiment we included a one-second break between processing and the presentation of the next letter stimulus, which the participants could use to rehearse. We hypothesized that distraction caused by the processing in the SRP condition interfered with this rehearsal process. During this period, distraction competes with rehearsal. Because the processing phase ended if there was less than 700ms remaining for a to be presented stimulus, this time was added to the inter-trial interval, making this phase on average 1.3s in duration.

Distraction was modeled as follows. During the processing phase of the task, memory retrievals are required to answer either the shoebox question or the self-referential question. The assumption of the model is that self-referential words are associated with operators that elaborate these words. Elaboration involves additional memory retrievals, and representing the results in working memory, which in its turn can prime additional elaboration.

The probability that elaboration happens is much larger in the SRP condition, which is modeled by strength of association between the SRP words and an elaboration operator.

Once the blank period starts, there is a chance that a distracting fact remains in WM. This distracting fact spreads activation to operators to further think about that fact, which have to compete with the task-relevant operators to rehearse the letters. A successful distraction will therefore impede mental rehearsal, and lower the working-memory score. Once rehearsal wins the competition, the distracting fact is removed from WM and rehearsal continues normally. It is worth mentioning that this implementation is thus not strictly based on a competition between goals but between operators. This was done mainly because distraction periods are so short that it hard to justify it as being an active goal. The term 'goal competition' was used because this is more common in the literature.

The only difference between the models of the SRP and non-SRP conditions is that the words in the shoebox condition do not spread activation to the distraction operators, while the SRP words do.

In PRIMs the speed at which operators execute is increased over multiple runs. This means that at first the operators execute relatively slow which is unrealistic for our participants who already have substantial real life experience remembering, retrieving and rehearsing items in memory. Therefore, the model is trained for 15 trials before the experimental run starts. The complete set of models is available from the author on request.

Model results

The model was run 500 times and the results were compared to the results of experiment 2. Figure 3 shows that the partial score is matched quite nicely by the model; showing a clear difference between the two conditions. Figure 4 shows that the model has some trouble matching the recall score per serial position. The primacy effect matches reasonably well but the recency effect is too strong in the model.

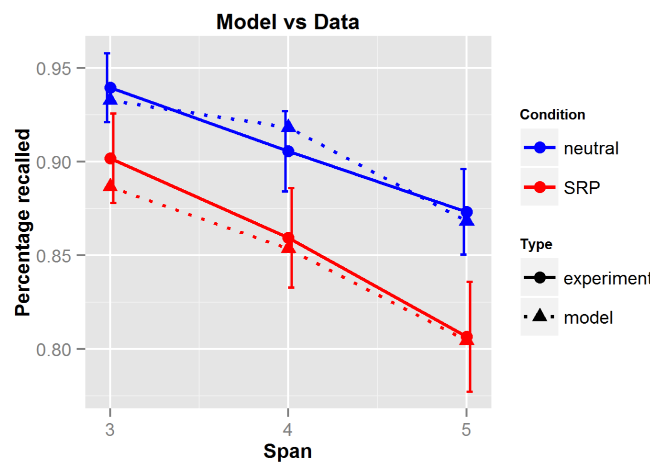

Figure 3: Comparison of partial-credit score between the experimental data (solid lines) and the model (dashed lines). 95% confidence interval bars are plotted for the experiment data only.

Effect of parameters

The model seems to do quite well in accounting for the observed difference in recall score between the two conditions. Various model parameters affect the model fits. Increasing the noise in memory tends to make the effect of span on score smaller, decreasing the slope between score and span. Decreasing the multiplication factor that scales memory retrieval time affects the difference between the two conditions since with a lower latency, the rehearsal process is faster allowing for more repetitions to be squeezed into the same amount of time. This benefits the neutral condition more than the SRP condition. Lowering the retrieval threshold increases the partial score for each span since with a lower threshold chunks are more easily recalled. This effect seems to be stronger for higher spans, most likely due to a ceiling effect at span 3.

Discussion

This study attempted to measure and model distraction caused by SRP on a memory task. To this extent two CWM span task experiments were conducted, comparing

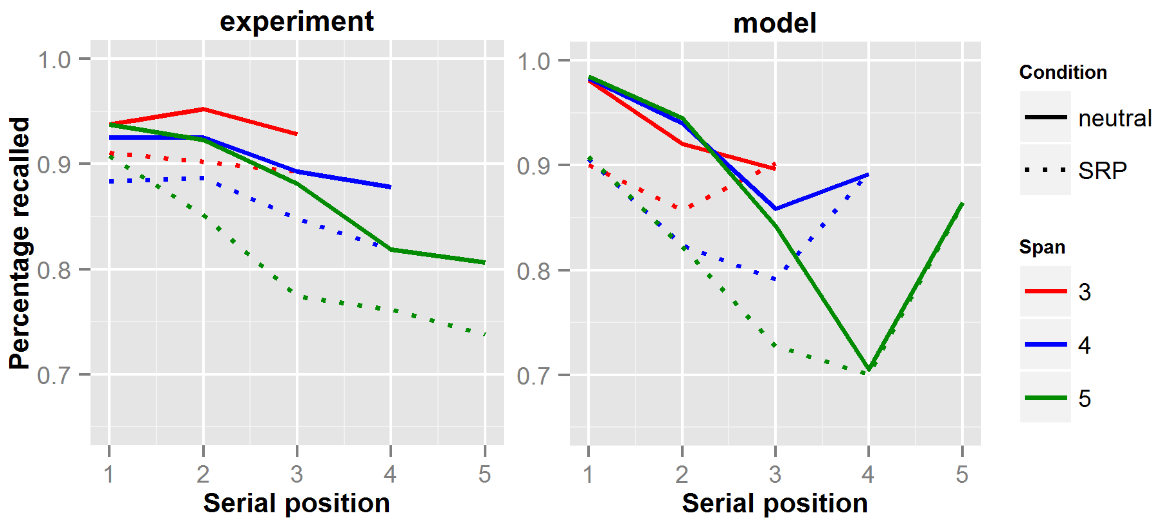

Figure 4: Percentage of successful recall by serial position for the experimental data (left column) and the model data (right column), separately for the SRP (dotted lines) and neutral (solid lines) conditions.

distraction by SRP (SRP condition) to distraction by other forms of processing (neutral condition) measured by the recall score on the CWM span task. The neutral processing consisted of letter recognition (experiment 1) and semantic processing (experiment 2). We found that in both experiments, SRP is associated with worse performance in the recall task than the other processing task. In experiment 2 we found that after including the average response time still a significant amount of variance in the recall score data could be explained by the condition factor. This was not so for experiment 1, most likely due to confusion between conditions by participants, see below. The experiment was modeled in PRIMs using a competitive goal approach in which distraction caused by SRP prevented letter rehearsal in the SRP condition. This model does quite well in accounting for the observed difference in recall score between the two conditions.

In the first experiment some participants reported that they sometimes forgot the condition associated with the current trial. This could happen due to the fact that the word stimuli for both conditions were the same and the condition was only indicated at the start of the trial. It is easy to detect when participants confuse the neutral with the SRP condition, as this means they would have scored at chance level. To see how often this might have happened we compared the number of neutral trials with <65% correct for both experiments. For experiment 1 this happened in 15 of the 900 trials (1.67%), and for experiment 2 this was 1 of 1044 trials (0.0958%). This indicates that indeed some confusion has occurred in experiment 1 but only in a small fraction of the trials. One can assume that these numbers are similar for the SRP condition (i.e. participants treating the SRP condition as the neutral condition), but this is hard to measure due to subjectivity of the responses in the SRP condition. Note that this doesn't negatively affect the main finding, if anything it only underestimates the true effects.

Further data analysis showed that the responses of the participants in the SRP condition could explain some of the level of distraction. The word pairs were labeled 1 and -1 for the positive and negative counterpart respectively. Responses were labeled 1 and -1 for yes and no respectively. Multiplying the responses by the word labels, averaging them per word, and then averaging this value for all words provides a basic indication about how positive a person thinks about himself, ranging from -1 (totally negative) to 1 (totally positive). This value was 0.6639 ± 0.224 for experiment 1 and 0.7102 ± 0.121 for experiment 2 (mean ± SD). Adding this 'positivity value' to the LME provided a significantly better fit for experiment 2 ($\chi 2$ (1) = 3.9773, p = 0.04612). Further exploring the nature of this effect—which was not found in experiment 1—is an interesting avenue for future research.

Our model does quite well in accounting for the effect of condition found in experiment 2, but it does have some limitations. Firstly, the model only accounts for retrieval errors, other types of mistakes such as transposition errors, item confusion or protrusion are not taken into account. Secondly, the model doesn't account for what is happening in the mind when it is distracted, in the current implementation the model just 'pauses' for a moment. This has the desired effect of preventing rehearsal but is not a plausible explanation of the mental processes happening during this time.

If the found decrease in recall performance is indeed caused by remaining emotions and thoughts after SRP, it gives rise to two interesting propositions. Firstly, this means that this effect could possibly be reduced by reducing SRP, for example, mindfulness training (Goldin, Ramel, & Gross, 2009). Secondly this means that performance in other types of secondary tasks (for example a processing task instead of recall) will also be affected by SRP.

In conclusion, we found that SRP has a negative effect on recall performance in a CWM span task. These findings can be accounted for using a cognitive model made in PRIMs, in which SRP causes a distracting fact to enter WM, which subsequently interferes with rehearsal by activating competing-but task unrelated-operators. If our mechanism is correct, this implies that the disruptive effect of SRP should also extend to other types of secondary tasks and that the effect might be reduced by actively increasing participant's SRP through for example mindfulness. These results show that CWM span tasks can be used as an objective measure of distractions caused by self-referential thought, and that PRIMs can increase our understanding of the mental processes underlying them. Together these will allow us to better understand and prevent undesired effects of mental distraction during important tasks.

Acknowledgments

This research was funded by ERC-StG grant 283597 awarded to Niels Taatgen and Marie Curie grant ACCDECMEM to Marieke van Vugt.

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