Modelling Mind wandering in ACT-R
(Bachelorproject)

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Abstract

Mind-wandering is the process of having task-unrelated thoughts. These thoughts can have both positive and negative effects during certain tasks. The contents of task-unrelated thoughts can vary between lightweight daydreaming and the more emotionally loaded rumination which we also take into consideration. Two experiments were performed to look at the differences between adaptive mind-wandering and executive failure: a Working Memory (WM) task and a Choice Reaction Time (CRT) task. The WM task was set up in a way that constant attention was required, while the CRT task did not need as much continuous involvement. Results showed a significant difference in how much participants were on-task between WM and CRT. On average, participants paid more attention during the WM task. Two models were built to describe this mechanically, one for the CRT task and one for the WM task.

Introduction

Having thoughts unrelated to the present moment, a common activity which every human being can relate to. For instance, what should I have for dinner tonight? Studies suggest that humans devote almost half of their waking time to mind wandering.(Killingsworth and Gilbert, 2010) Mind wandering is defined as self-generated, task unrelated thought. Self-generated thoughts are thoughts that are stimulus-independent, the creation of thoughts that are not the consequence of perceptual events. For instance, while filling in your tax refunds thinking why am I doing this? Or thinking about the future while laying in bed. These examples can be differentiated by the presence of external perceptual stimuli generating the contents of the thought. In the tax example, the action, reflecting on why you are doing this, was the cue for the self-generated thought. But in the bed example there was no such cue present. Perceptually guided thoughts, in contrast to self-generated thoughts, are thoughts that are the consequence of what is perceived. Two examples are thinking about what to visit while planning a holiday and being distracted by hearing your name.

Mind wandering is a process that takes place spontaneously and is not induced by external stimuli. It is known that there are a number of causes that can manipulate the frequency of the wandering of the mind. Mind wandering is for instance more common with fatigue, alcohol consumption and nicotine craving.(Sayette, Reichle, and Schooler, 2009) (Sayette, Schooler, and Reichle, 2010) It is less common when a task is conducted which

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makes active use of the working-memory and with people with a higher working-memory capacity. (McVay and Kane, 2009)
The wandering of the mind can be monitored in a number of ways. With functional magnetic resonance imaging (fMRI), brain activity is measured by detecting changes in blood flow. The activity of the default mode network (DMN) increases prior to mind wandering.(Christoff, Gordon, Smallwood, Smith, and Schooler, 2009) The DMN is a network of brain regions that are active when the brain is not focused on the outside world. It was also found that brain regions used in cognitive control are also active. Implying that mind wandering also occupies the brain regions related to working memory. (Christoff et al., 2009) Pupil dilation is also related to mind wandering. Cognitive events are known to dictate pupil dilation. (Kahneman, 1973) Mind wandering is responsible for pupil expansion, underlining the cognitive load that mind wandering causes. (Franklin, Broadway, Mrazek, Smallwood, and Schooler, 2013) A third way to monitor mind wandering is the experience sampling method. With this method, test subjects are asked to stop their task at random times and dictate their thoughts at that right moment. This reports the content of the concious activity of the test subjects at certain moments. From this, it can be derived if the test subject had task-related or self-generated thoughts. Furthermore, more specific content about the thoughts can be gathered. For instance, if the test subject was thinking about the past, present or future. Or if the thoughts were negative, neutral or positive. With this information, types of mind wandering can be differentiated, like rumination versus daydreaming.
Rumination is defined as persistent, re-cyclic, depressive thinking.(Papageorgiou and Wells, 2004) Often, these thoughts are accompanied with negative emotion and unhappy moods are related to an increase in past-related mind wandering. (Smallwood and O'Connor, 2011) Mind wandering consumes executive resources, drawing attention away from the performed task, but for which purpose? As noted above, the DMN shows increased activity prior to mind wandering. These brain regions also show heightened activity when resting and during tasks that do not need a high level of cognitive activity. (McVay and Kane, 2010) This activity can be accredited to autobiographical planning, evaluating life goals and creative problem solving, some advantageous effects of mind wandering. (Klinger, 2009) (Mooneyham and Schooler, 2013) This is also known as the perceptual decoupling theory, the disengagement of attention from perception for engagement in internal cognitive processes. (Schooler, Smallwood, Christoff, Handy, Reichle, and Sayette, 2011)
To find out if the wandering of the mind increases during tasks that do not need a high level of cognitive activity and decreases when the working-memory is actively used, an experiment was set up. Participants engaged in two different tasks, the Choice Reaction Time (CRT) task and the Working Memory (WM) task. In the CRT task the participant had to decide if a green coloured target number, depicted on a screen, was even or odd. In the WM task participants had to decide if the number preceding the target, a red question mark, was even or odd. In the CRT task it is not crucial to process every stimulus depicted on the screen, only the target is necessary to correctly respond. This means that this task does not require continuous cognitive processing, hypothesised is that mind wandering is induced. While for the WM task it is important to remember if every stimulus is even or odd because it is not known when the target will appear. This requires a continuous occupation of the working-memory, therefore it is hypothesised that mind wandering decreases. To

acquire more explicit knowledge about mind wandering in the CRT and WM tasks, two Adaptive Control of Thought-Rational (ACT-R) models were constructed. These models were built upon a Sustained Attention to Respond (SART) ACT-R model, used to study mind wandering during the SART task. (van Vugt, Taatgen, Sackur, Bastian, Borst, and Mehlhorn, 2015) During the CRT and WM task experience sampling was used to identify the content of the participants' thoughts. This information is meaningful to address the following question. Are emotionally-loaded negative ruminations responsible for longer and deeper mind wanders? Hypothesised is that ruminative mind wanders cause a higher variance in reaction time. If negative ruminations indeed cause longer and deeper mind wanders the ACT-R models will be adjusted accordingly.

Method

Experiment

Twenty-four students from the Rijksuniversiteit Groningen were invited to do an hour-long "Numbers Decision Experiment" behind a personal computer. Each one of the participants received a fee of 10 Euro for participation. The session consisted of twelve blocks consisting of six CRT and six WM tasks conducted alternately. The order was counterbalanced, participants with an odd number started with the CRT task and participants with an even number started with the WM task (The first participant started with the CRT, the second with the WM).
Both of the tasks consisted of a stream of numeric digits, 1-9, presented on the computer screen for 1000 ms, in black colour. These stimuli were separated by a fixation cross shown for a random time between 900 and 2100 ms. At random moments during the experiment experience sampling probes, or thought probes were presented. These probes were also presented on a computer screen and consisted of five questions, depicted in *Table 1.* The questions were answered by using the mouse and moving a slider on a scale system from -50 to +50. The -50 was used for "not at all" and +50 for "exclusively". Four times per block the thought probes were presented. At the beginning of each session the participants first conducted two practice blocks, one for the CRT task and one for the WM task. In these two practice blocks thought probes were presented once per block. The participants were informed they could ask questions during and after the practice blocks, but not during the real experiment.
In the Choice Reaction Time (CRT) task the participants monitored the screen for the presence of a target, this target was a green coloured numeric digit, 1-9, almost identical to the black coloured stimuli. Whenever this target occurred, participants were asked to determine if it was odd or even. Participants responded by pressing the 'o' key on the keyboard for odd and the 'e' key for even. In one CRT block twenty targets occurred. In the Working Memory (WM) task the participants also monitored the screen for the presence of a target. In the WM task this target was a red coloured question mark. This time, participants were asked to determine if the digit preceding the target was odd or even. Participants also responded with the "o" and "e" keys on the keyboard. In the WM task the target was also presented twenty times per block. The Choice Reaction Time and Working Memory experiments were coded in PsychoPy 2 and can be downloaded for review from the following link. `https://www.dropbox.com/s/q6kljld3ewh90xf/WM_CRT_V4.py`

Where you thinking about the task or something else?
How much were you thinking about other people?
How much were you thinking about the past?
How positive were your thoughts?
How aware were you of whether you were on task?

Table 1: The five thought probe questions

Models

The models were developed using the cognitive architecture Adaptive Control of Thought-Rational (ACT-R), version 6.0. (Anderson, Bothell, Byrne, Douglass, Lebiere, and Qin, 2004) ACT-R is a theory of the structure of the brain and can be used to explain and predict performance in psychological tasks such as the Choice Reaction Time task and the Working Memory task. The brain is divided in different brain structures, called modules or buffers. These modules can be divided into two kinds, the perceptual-motor modules and the memory modules. The perceptual-motor modules are the architectures' connection to the real world, the actuators and sensors. The visual and manual buffers are the main perceptual-motor modules used in this study. Two types of memory modules exist in ACT-R, the declarative memory and the procedural memory. The declarative memory contains declarative knowledge represented by chunks. Chunks represent pieces of explicit knowledge, or facts, like: 'the number 2 is even'. The procedural memory is composed of production rules. These productions are formal notations of the interaction of the different cognitive structures, they control the behaviour of the architecture. Productions represent tacit knowledge, how we do thinks. They can be represented as if-then rules. For instance: if the goal is to respond and the number on the screen is even then press 'e'.

The Choice Reaction Time model and the Working Memory model were developed using a similar ACT-R mind wandering model that examines the SART task. (van Vugt et al., 2015) This task, the Sustained Attention to Respond Task, involves participants pressing a key when a non-target is presented and withhold pressing when a target is presented. For instance, a stream of digits from 1 till 9 is shown, where 3 is the target. Participants have to press a key on a keyboard at every presentation of a digit, except the number 3. The SART task is fairly similar to the Choice Reaction Time task explained above. The CRT task has one extra cognitive production, the retrieval of a number being odd or even. The model of the SART task is based on another ACT-R mind wandering model which formulates mind wandering as two competing strategies, one for paying attention, being on-task and one for getting distracted. (Peebles and Bothell, 2004) The SART ACT-R model has two competing goal productions, one to attend the task and one for distraction. The CRT and WM models in this study have the same strategy for the modelling of mind wandering. The models both start the task by attending to the stimulus presented on the screen, so paying attention.

In the Choice Reaction Time task model, the stimulus will be processed and identified. It will check the colour of the stimulus and react with the appropriate action. When the colour of the stimulus appears to be green, the model retrieves information about the number being odd or even from the declarative memory, and presses the appropriate key on the key-

board. When the stimulus is black coloured, the model does not respond and will return to check what the goal is, to attend or being distracted. If the stimulus is a thought probe, formalised by the letter 'Q', the model responds only if it is on-task.
The Working Memory task model acts slightly different at the presentation of a stimulus. The stimulus will be processed, identified and stored in the imaginal buffer. After this stimulus is stored in the imaginal buffer, and the target stimulus is presented, a red question mark, information about the previously processed stimulus is retrieved and the corresponding key is pressed. The responses for the thought probes and the no-response work similarly.
After the presentation of the stimulus the models will continuously check the current goal, if they are attending or distracted. The current goal is determined by the level of activation, the item with the highest activation will prevail. The level of activation is adjusted by the length of time passed since the item was lastly retrieved from the declarative memory. The activation goes up when an item is retrieved and gradually decays when time passes. The activation of the attend goal rises at the start of the task and decreases until the activation for the getting distracted goal is higher. When this happens the goal of the model changes and it starts mind wandering.
The mind wandering is formalised by using a so-called thought-pump. This thought pump retrieves memories from the declarative memory. These memories are represented by the model as chunks. The memories will continue being retrieved until the model remembers to attend the task. This happens when a memory is retrieved which activates the remember to attend production. This causes the retrieval of the attend goal and therefore raising the activation. Resulting in the model return attending to the task.
While the models are mind wandering they are not paying attention to the stimuli presented on the screen. For the WM task, not paying attention on the screen results in a lower accuracy because the number preceding to the question mark is not stored in the imaginal buffer. Not paying attention also causes a delayed reaction, so a higher reaction time. The accuracy of the CRT task should be affected less by the wandering of the mind than the WM task, because the stimulus is still on-screen when the model returns to the task. Not paying attention in the CRT task will result in a higher reaction time.
Therefore it is very plausible to measure mind wandering in terms of the response time coefficient of variability. The more a person gets distracted, the higher the variability in response times. This theory is substantiated by other studies about mind wandering and response times. (Bastian and Sackur, 2013) The response time coefficient of variability is calculated by dividing the standard deviation trough the mean. The results of this study will be provided in the next section. The CRT model can be downloaded here: `https://www.dropbox.com/s/spkq033fhn1lbpk/MW_CRT_FINAL.lisp` and the WM model here: `https://www.dropbox.com/s/cviqwco2pp1ev7o/MW_WM_FINAL.lisp`

Results

Thought Probes

Five paired T-tests were performed on the thought probes presented during the experiment. This was done to learn whether there was a significant difference between the answers in the Choice Reaction Time task and the Working Memory Task. The participants significantly thought more about the task in the WM task than in the CRT task ($t = 2.8936$, $df = 22$, p-value < 0.05). In the WM task the participants were also significantly

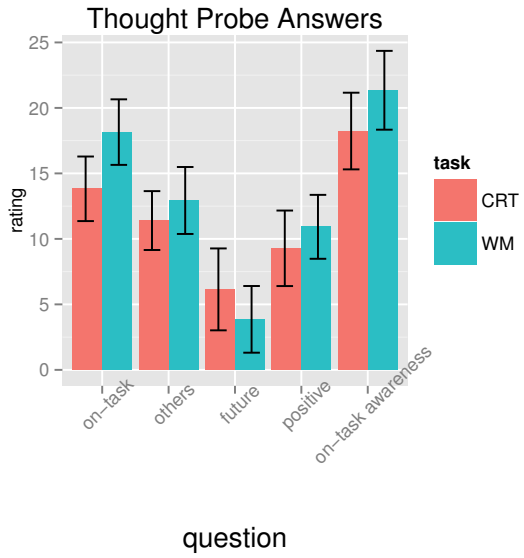

Figure 1: The mean of the answers to the thought probes during the experiment.

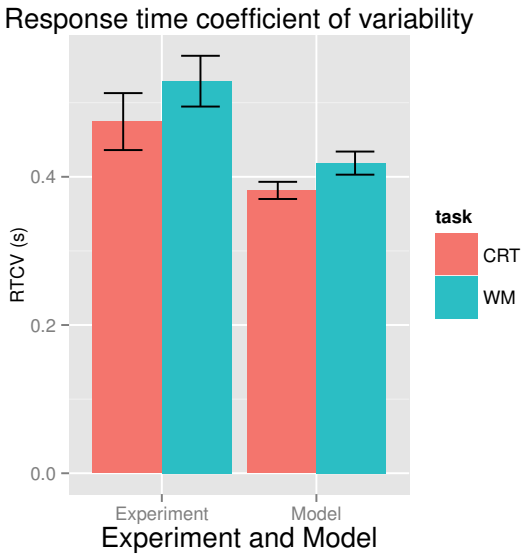

Figure 2: The response time coefficient of variability for the experiment and the model. The error bars represent the standard error.

more aware that they were on task than in the CRT task (t = 2.4044, df = 22, p-value < 0.05). There was no significant difference found in the means for the question if the participants were thinking about other people (t = 1.1348, df = 22, p-value > 0.05). The same for thinking about the future (t = -1.296, df = 22, p-value > 0.05), and the question about the positivity of thoughts (t = 1.4962, df = 22, p-value > 0.05). The answers of the questions in *Table 1* are depicted in *Figure 1*.

Response time coefficient of variability

As mentioned in the methods section, to compare the degree of mind wandering from the experiment and the models the RTCV was used. As depicted in *Figure 2*, the RTCVs in the experiments are higher than that in the models. For the CRT task the RTCV of the experiment was (RTCV = 0.4744861) and the RTCV of the model was (RTCV = 0.3816351). In the WM task the RTCV of the experiment was (RTCV = 0.5290317) and of the model it was (0.4184595).

To see if the negativity of thoughts have an influence on the response time coefficient of variability two tests were performed, one for the WM task and one for the CRT task. The RCTV of every block preceding a question block was calculated and compared to the answer of question 4. Then a linear regression analysis was used to determine if the value of the answer of question 4 influenced the RCTV. For the CRT task a p-value of 0.1252 was obtained, for the WM task the p-value was 0.7902. This indicates that we can not reject the null hypothesis for both of the tasks.

Accuracy

To further compare the mind wandering model to the real world experiment the accuracy was examined. The accuracy of the CRT task in the experiment was (ACC = 0.9528986) and

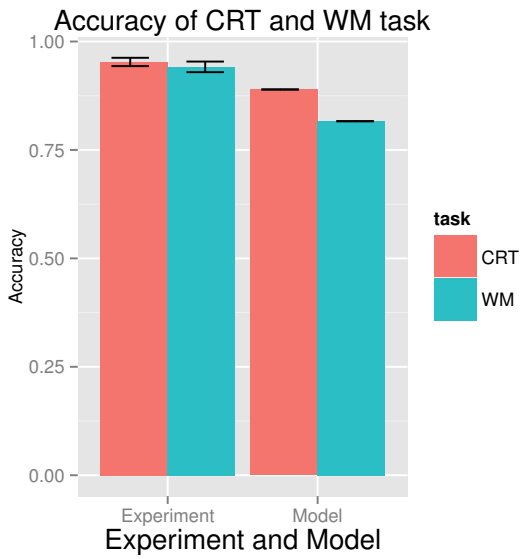

Figure 3: The accuracy for the experiment and the model. The error bars represent the standard error.

for the model it was (ACC = 0.8894243). For the WM task the accuracy in the experiment was (ACC = 0.9415761) and for the model the accuracy was (ACC = 0.8162617). The difference in accuracies between the experiment tasks are smaller than that of the model. The results are depicted in *Figure 3*.

Discussion

This study set out to explore difference in mind wandering in the CRT and the WM task and modelling this in ACT-R. Also we explored a possible relation between negative rumination and the intensity of mind wandering. Hypothesised was that there is a higher response time coefficient of variability in the CRT task than in the WM task. The results indicate otherwise, the RTCV was higher in the WM task than in the CRT task. Also no relation was found between the negativity of the thoughts and the RTCV. The answers to the thought probes do indicate a significant difference between the CRT and WM task for mind wandering. For the comparison of the experiment and the models two parameters were used, the RCTV and the accuracy. For both parameters a lower value was found in the model than in the experiment. But, as the figures in the results section show, the relation between the CRT and WM model are similar. /subsection*Comparison of RTCVs of two different tasks In this study the RTCV of two different tasks were used to compare the degree of mind wandering for both tasks. Response times in the two tasks are dependent of more factors than only the degree of mind wandering. In the working memory task, high response times could result from the doubting if the remembered number was the correct one. This doubting could be responsible for response times higher than one or two seconds. In the CRT task doubting is not relevant because the correct response can be determined from the on the screen presented stimulus. So the assumption that the RTCV can be used to address the difference in mind wandering for two tasks seems to be incorrect.

Experiment and models

As can be observed in the results section, the RTCVs of the models are lower than that of the experiment. The response time coefficient of variability is not just determined by the degree of mind wandering, but can be affected by human feelings, like uncertainty. Doubt is a thing not implemented in this ACT-R model. The accuracy of the models is also lower than that of the participants. This is probably due to the standard response production implemented in the CRT model, when distracted the model gives a default response. The model should never give this default response because the target is still presented on the screen when the model stops mind wandering and starts

paying attention to the task again.

Possible deficiencies

The experiment was conducted under twenty-four participants, all students which got a fee for participating. While conducting the experiment some participants were finished in a way shorter period of time than others. This could indicate that they did not took the time to meta-cognitively evaluate their thoughts before answering the thought probes, especially the questions about the content of the thoughts. The experiment took about over an hour. An hour was chosen to induce mind wandering during this long time of executing two boring tasks. This may increase mind wandering, but also increases the chance of participants wanting to finish quickly. Determining if the participant is mind wandering is easier than thinking about what the content of these thoughts is.
This study tried to find a difference between adaptive mind wandering and executive failure. The results from the thought probes indicate that there indeed was a difference in the degree of mind wandering. Hypothesised was that this was due to continuous use of the stimuli being stored in the imaginal buffer in the working memory task. This was modelled but only compared to the experiment by accuracy and the response time coefficient of variability. This seemed not to be a proper way for comparison. A step was made in the right direction. The model is there, when thought probes will be added to the model a proper comparison is possible.

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