A Computational Model of Mind Wandering

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Abstract

We present a computational cognitive model of mind wandering, an important cognitive phenomenon whose mechanisms are involved in insight, problem-solving, and creativity. The model posits that mind wandering begins when one is not engaged in goal-oriented cognition, whether when between tasks or when in the middle of a task but not actively thinking about one's goal. At such times, the model thinks about other, highly-activated thoughts in memory. This model sheds light on both how task-oriented and more basic cognitive processes interact, as well as how mind wandering content is generated; both unresolved questions for mind wandering research. We compare our model against data presented by McVay and Kane (2013), who induced mind wandering in a laboratory setting by embedding participants' personal goals and concerns in a lexical SART task. Overall, our model matched the data's mind wandering rates very well. We discuss implications and future work on the model.

Keywords: mind wandering; spreading activation; priming; cognitive models

Introduction

Mind wandering is typically viewed as an undesirable phenomenon. A wandering mind means that one is not concentrating on the task at hand, and instead is using valuable mental resources to engage in fanciful thought. It has been shown to disrupt reading comprehension, negatively affect one's mood and affect, and is correlated with lower performance on general aptitude tasks (Mooneyham & Schooler, 2013; Schooler et al., 2014). On the other hand, however, the processes of mind wandering may also be essential to key mental phenomena such as insight, creative thought and planning for the future (Gabora, 2010; Baird et al., 2012; Stawarczyk, Majerus, Maj, der Linden, & D'Argembeau, 2011). While mind wandering may sometimes compromise one's ability to perform one's current work, then, its mechanisms often appear to engage for the benefit of future tasks and performance. This makes mind wandering important not only to psychological and behavioral researchers, seeking to understand how mind wandering affects task performance and attention, but also to cognitive scientists and roboticists, who may also see mind wandering processes as tools to implement in cognitive systems in order to foster problem-solving, creativity, and innovation.

Mind wandering is typically measured indirectly or subjectively, with study participants self-reporting mind wandering either in response to probes during an experiment, or by recording unprovoked thoughts during the day in a diary; these measures, then, can be used in combination with other metrics such as fMRI, task performance, or gaze tracking, to help understand the phenomenon (Schooler et al., 2014). Such evidence has revealed that a different set of regions of the brain, collectively termed the *default mode network* (DMN), is more active when people report mind wandering than when they report exhibiting task-directed thought (Schooler et al., 2011). Further, its activation is typically associated with a decline in activation of areas associated with task-oriented thought (e.g., areas associated with *executive control*); this, and other data, have led many to hypothesize that mind wandering is correlated with a failure of executive control functions (Schooler et al., 2011; Mason et al., 2007).

The underlying details of this correlation, however, are still open for debate: it is not always clear how mind wandering begins when executive control functions are presumably in use; and it is difficult to study mind wandering at this level since it, by definition, is a subjective experience that participants cannot be directed or encouraged to perform as part of their task. Furthermore, it is not generally well understood how mind wandering content is produced (Schooler et al., 2011). One experiment that investigated this successfully induced mind wandering in a repetitive, lexical SART task performed in a laboratory setting by embedding words relevant to participants' own personal goals and concerns in the task (McVay & Kane, 2013). This experiment showed that mind wandering is more likely to occur when subjects are subconsciously primed in this way, by their own real-life goals and concerns, suggesting that environmental cues can affect how and when one mind wanders.

We have developed a cognitive, computational model of mind wandering that explores these issues at the process level. Our model posits that mind wandering begins during natural breaks in task-oriented thought; e.g., it begins when one is not actively reasoning about one's goal, even if one is working towards it. Our model also hypothesizes that mind wandering begins only when there is a thought active enough in memory to be easily and quickly thought about; this activation is heavily influenced by the contents of one's working memory, such as environmental cues. We compare our mind wandering data against the experimental data from (McVay & Kane, 2013), and show a strong match, accounting for their mind wandering rates with $R^2 = 0.984$. Overall, our model supports the idea that mind wandering arises when executive control functions fail, and proposes a mechanism through which mind wandering content is generated, enabling those who are interested in promoting creativity, problem-solving and innovation in cognitive systems to better understand mind wandering's underlying mechanisms.

Experiment

We evaluate our mind wandering model by comparing it against the experimental data of two of the experiments from (McVay & Kane, 2013). This study induced mind wandering in a series of experiments held in a laboratory setting by embedding words associated with participants' personal goals and concerns within a lexical Sustained Attention to Response Task (SART, a go/no-go task (Robertson, Manley, Andrade, Baddeley, & Yiend, 1997)). In this task, participants press the space bar if the stimulus is lower case (*non-targets*, as most stimuli are), and withhold pressing a key if the current stimuli is upper case (*targets*). Approximately 11% of stimuli were targets. Each stimulus appeared for 300ms, and was followed by a 900ms mask. Occasionally during the experiment, participants would be given a thought probe, where they reported the degree to which their thought was task-related or not. All responses indicating off-task thought was considered to indicate mind wandering.

To accomplish this, each experiment consisted of two sessions that the participants were led to believe were unrelated. In the first session, participants filled out a set of surveys designed to collect information about their personal goals and concerns. Then, two days later, participants returned to perform the SART task. The participants' SARTs were then personally customized: occasionally, triplets of words were shown in sequence, as non-targets, that corresponded to participants' personal goals and concerns (personal goal, or PG, triplets), as reported on the surveys during the first session. For example, if a participant had said he/she needed to give his/her two dogs a bath, three sequential words in their SART might have been "wash" – "two" – "pets." The SART also contained goal-related triplets that were unrelated to the participants' individual goals, such as "close" – "wooden" – "door" (other goal, or OG, triplets).

Each participant's experiment included two triplets for each type, for a total of four word triplets, that were presented at various times throughout the experiment. A post-study questionnaire showed that participants generally did not notice any overlap between the two sessions and did not, consciously, realize they were being primed by their own goals.

The original study performed four similar versions of this experiment; we model two of them here, Experiment 1 and 3. Note that we elected to model Experiment 3 instead of 2 because, although nearly identical, Experiment 2 was the only experiment in this study that included thought probes unassociated with targets (and which the authors did not analyze). In Experiment 1, 62 participants saw 810 trials, with each of the four word triplets appearing 9 times. In this experiment, the type of triplet presented to the participants strictly alternated, beginning with OG. One, three or five non-targets after each triplet, whether OG or PG, there was a target, followed by a thought probe.

In Experiment 3, 56 participants saw 1080 trials, with each of the four word triplets appearing 12 times. The ordering of triplet type presented varied (it did not strictly alternate as in Experiment 1). One non-target stimulus after each triplet, whether OG or PG, there was a target, followed by a thought probe. The exact stimuli order for both experiments can be found in (McVay & Kane, 2013).

The study measured both the rates of mind wandering associated with the thought probes following a word triplet, as well as the accuracy rates of participant responses to the targets immediately preceding the probes. For both experiments, mind wandering rates were significantly higher after PG triplets as compared to after OG triplets: a 6.7% difference for Experiment 1, and a 5.9% difference for Experiment 3. These effects strongly suggest that cuing subjects with their personal goals and concerns can, in fact, induce mind wandering during an unrelated task.

There was also a significant difference in accuracy for both experiments, but in different directions. In Experiment 1, target accuracy was significantly higher after OG triplets, with an effect size of 5.6%. In contrast, in Experiment 3, target accuracy was significantly higher after PG triplets, with a smaller effect size of 3.7%. Interestingly, combining the data across experiments was inconclusive, suggesting no effect overall. The authors suggest that this means that the PG triplets may not reliably derail participants' train of thought strongly enough to decrease accuracy. We take this into consideration when building our model, below.

Model

Our cognitive model of mind wandering has two different aspects: performing the SART task, and modeling mind wandering. We first describe the general principles of these two components of the model. Then, we give further details of how these components are realized within the computational cognitive architecture we use, ACT-R/E, and discuss how our model's principles interact with the cognitive architecture to make specific predictions about mind wandering.

Our model performs the SART task using an existing, utility-learning based procedure that has been shown to successfully model human SART performance (Peebles & Bothell, 2004). It has two strategies for responding to stimuli: either just "clicking" when a stimulus appears, without fully processing whether the stimulus is upper or lower case, or "checking," where the stimulus is fully processed, and its case evaluated, before a response decision is made. "Clicking" results in faster response times, but will result in errors on target stimuli; "checking" takes longer, since it requires waiting for the stimuli to be added to working memory before responding, but results in perfect performance. Initially, both strategies have equal chance of being chosen and so are employed with roughly equal frequencies; over time, however, the faster response time of "clicking" leads it to surpass "checking" in its expected usefulness, despite occasionally resulting in errors. In general, "checking" requires goal-driven control (the model must perform place-keeping operations while, for example, it processes the case of the stimulus word), but "clicking" does not (it clicks in response to changes in its visual field without further thought).

At the core of our model is the claim that mind wandering occurs when the model is not actively thinking about its goal. Such cases can happen when the model does not currently have a goal; or, when it does have a goal, but is not explicitly thinking about it (such as waiting for something goal-related to occur, or waiting for a memory to be retrieved before it can continue with its task). At such times, the model begins to mind wander if there is a thought in memory that has a high enough activation to be easily and quickly thought about (or, if the model is already mind wandering at such times, it continues to mind wander). The model thus implies that, when mind wandering, the model's thought processes and perceptual processes are disconnected. A model can mind wander, for example, while still seeing and reacting to the world, as long as its vision and manipulative processes do not require goal-oriented thought; this is supported by other, previous work (Schooler et al., 2011).

Once the model requires explicitly thinking about its goal in some way, such as if the model responds to a stimulus using the "check" strategy, mind wandering ends. This is accordance with the conclusions of the authors of the study, which suggest that the PG triplets, while inducing mind wandering, do not sufficiently divert one's attention from the task to decrease accuracy.

The model includes two goals in memory that correspond to the two PG triplets of the experiment. While in actuality the relationship between these goals and the words in the corresponding PG triplets may be quite complex (e.g., connecting "dogs" to "pets", relating "give a bath" to "wash"), we avoid this complexity by simply creating explicit *associations* between the words in the triplet and the goal they collectively represent. These associations play a key role in our model's mind wandering predictions by boosting the probability of mind wandering while seeing a PG triplet, as we will describe further below.

Model Architecture

The model was developed within the cognitive architecture ACT-R/E (Trafton et al., 2013). At a high level, ACT-R/E is an integrated, production-based system (Anderson, 2007). At its core are the contents of its working memory; they indicates, for example, what the model is looking at, what it is thinking, and its current goal. At any given time, there is a set of *productions* (if-then rules) that may fire because their preconditions are satisfied by the current contents of working memory. From this set, the production with the highest utility is selected to fire. The fired production can either change the model's internal state (e.g., by updating its goal) or its physical one (e.g., by pressing a key on a keyboard). To calculate production utilities, ACT-R uses an elaboration of the Rescorla-Wagner learning rule and the temporal different algorithm (Fu & Anderson, 2006), which has been shown to be related to animal and human learning theory. When a reward is given (such as if the model successfully responds to a non-target), it is propagated back in time through the rules that had an impact on the reward being earned. This propagation process shifts utilities over time such that productions that more often and more quickly lead to reward have a higher probability of firing. Random noise can also be added in during execution to affect production selection.

Working memory contents take the forms of thoughts, or memories. In addition to the symbolic information represented as part of these memories, memories have activation values that represent their relevance to the current situation. Activation has three components: activation strengthening, spreading activation, and activation noise. Activation strengthening is learned over time and is a function of the frequency and recency with which the memory has been in working memory in the past. It is designed to represent the activation of a memory over longer periods of time.

Spreading activation, or priming, is temporary and spreads from the current contents of working memory, distributing activation along associations between the thoughts in working memory and other memories (Hiatt & Trafton, 2013). Activation also spreads, less strongly, from items that were recently in working memory, even if they are not currently being thought about (Thomson, Bennati, & Lebiere, 2014). This allows spreading activation to capture correspondences between memories that are expected to be relevant at roughly the same time, as well as memories that are semantically related (such as the PG triplet words and the corresponding personal goal or concerns).

Noise is a random component that models the noise of the human brain and is based on a logistic distribution with mean of 0. It is a transient value that changes each time it is used. Together, these activation values have been shown to be an excellent predictor of human declarative memory (Anderson, Bothell, Lebiere, & Matessa, 1998; Anderson, 1983; Schneider & Anderson, 2011).

ACT-R/E supports distinguishing between goal-oriented cognition and non goal-oriented cognition via the interaction between working memory and productions. Recall that productions have specific preconditions, which may or may not refer to a goal in working memory. Therefore, for the purposes of mind wandering, there are two types of productions in an ACT-R/E model. The first type of production, such as that used by the "click" strategy, does not refer to the goal, and so it can fire either when there is no goal in working memory, or when there is but the production does not refer it. The second type of production, used primarily by the "check" strategy, explicitly refers to the goal currently in working memory (*i.e.*, modifies the goal, removes the current goal, or adds a new goal).

Mind wandering accesses thoughts in this architecture very similarly to how models access memories from long-term memory. The time it takes to access a memory (i.e., the time between when a memory is requested and when it is thought about) is inversely related to its activation; thus, highly activated thoughts will be accessed very quickly, whereas thoughts with a lower activation take longer to think about. Memory access also has an associated threshold, determining how easily and quickly a memory must be able to be accessed in order to be thought about at all. In our model, any time a production fires that does not refer to the goal, the model attempts to begin to mind wander if a memory has a high enough activation to be accessed (if the model is already mind wandering, it simply continues to do so). If the production refers to the goal in working memory, mind wandering, if it is currently occurring, ends, including canceling any ongoing attempts to access a memory.

ACT-R/E models interact with the world using ACT-R/E's built-in functionality for interacting with the world. Models can view visual items on a simulated monitor; they can act on the world by pushing keys on a simulated keyboard and clicking a simulated mouse.

Model Explanations

While looking at a word during the SART, the word appears in working memory, and so, as we described above, activation is spread from current and recent words to associated thoughts in memory. Thus, by the time the model sees the third word of a PG triplet, the first, second and third words are each spreading activation to the associated goal in memory. Due to this priming, the model explains that it is more likely to mind wander after seeing a PG triplet because it is more likely that a thought in memory will have a high enough activation to be easily and quickly thought about via mind wandering.

The model also explains why mind wandering after a PG triplet will be slightly higher for Experiment 3 than for Experiment 1. This is because there is are only two stimuli between the PG triplets and the probe for Experiment 3, instead of the 2-6 for Experiment 1, resulting in a higher chance that any mind wandering occurring after a PG triplet will be interrupted by goal-oriented thought. This explanation is additionally supported by a secondary analysis of the experiment, which revealed that the main differential between the PG and OG conditions for Experiment 1 occurred when the probe was only 2 stimuli away from the PG or OG triplet.

With respect to accuracy, the model explains why the accuracy rate for the PG condition is lower than the accuracy rate for the OG condition in Experiment 1. As we have discussed, because of utility learning, the click strategy becomes more preferred than the check strategy as the experiment progresses. Because of the strict alternating of OG and PG triplets in the first experiment, then, this means that PG condition overall will slightly favor the click strategy compared to the OG condition. This in turn leads us to expect more errors in the PG condition than in the OG condition. Because the PG and OG conditions are evenly interspersed throughout Experiment 3, the model predicts the accuracies of the PG and OG conditions will be equal, barring noise effects, in Experiment 3.

Model Results

The model performed Experiments 1 and 3 from (McVay & Kane, 2013) 64 and 56 times, respectively, to correspond to the number of participants in each original experiment. Activation noise and utility noise caused variation between model runs. In terms of parameters, activation noise was set to 0.25, and utility noise was set to 0.1, both fairly modest noise values. The utility learning rate was set to 0.2. The activation strengthening (also called the base level learning) decay parameter was set to 0.4 instead of its default of 0.5. The mind wandering activation threshold parameter was set to 0.7, which is higher than the standard memory activation threshold of 0.0. All other parameters were set to their default values.

The experiment and model results are shown in Figures 1 and 2. The model had an increased mind wandering rate of 3.8% for the PG condition vs. the OG condition for Experiment 1, and 4.3% for Experiment 3. It also had a decreased accuracy rate of 4.1% for the PG condition vs. the OG condition for Experiment 1, and 0.4% for Experiment 3. Overall, the model matched the mind wandering data extremely well, with an R^2 of 0.984. Its R^2 for accuracy rate was less strong, at 0.612. This is, in large part, because we do not predict a meaningful difference in accuracy rates for Experiment 3, as described above. We are comfortable with this prediction despite its relatively poor match, as it seems to match the data combined across the entire study, which, as we have discussed, showed no significant effect in accuracy between the PG and OG conditions.

Discussion

In this paper, we have described a computational, process model of mind wandering that furthers our understanding of mind wandering mechanisms and contents. In our model, mind wandering begins during natural beaks in task-oriented thought, and occurs only when there is a thought active enough in memory to be easily and quickly thought about. Thus, we claim that mind wandering can be heavily affected by task structure (e.g., are there gaps in goal-oriented processing during the task?) and environmental cues (e.g., are there any concepts highly primed by the environment or aspects of the tasks?). This deeper understanding of mind wandering is important to scientists who see mind wandering mechanisms and processes as tools to implement in cognitive systems in order to foster problem-solving, creativity, and innovation.

As we discussed in the beginning of this paper, a deeper layer to this in the mind wandering literature is the notion of executive control, or purposefully keeping one's train of thought on-task even when mind wandering is possible.

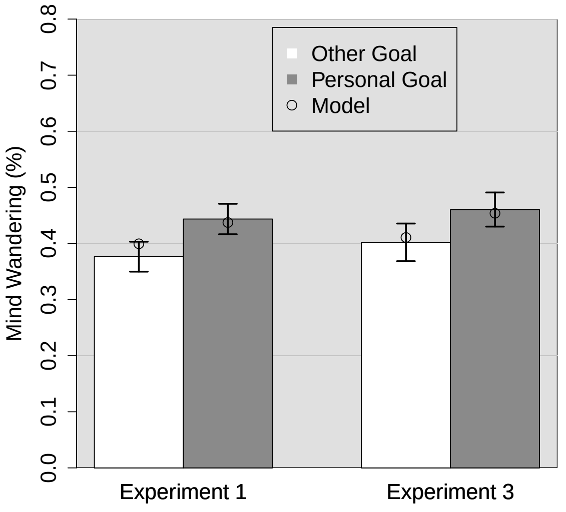

Figure 1: Mind wandering results for Experiments 1 and 3 from (McVay & Kane, 2013). Reports the percentage of thought probes to which participants responded they were mind wandering. The dots are the results from our model; the bar and errors bars show human participant results.

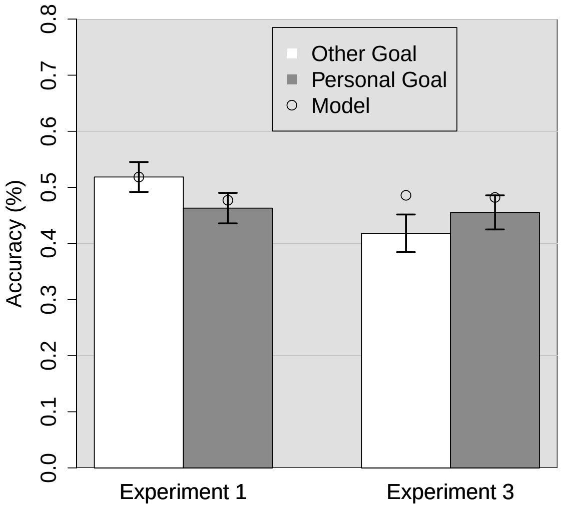

Figure 2: Accuracy results for Experiments 1 and 3 from (McVay & Kane, 2013). Reports the percentage of target stimuli that were correctly responded to. The dots are the results from our model; the bar and errors bars show human participant results.

While this work does not directly account for executive control, our model implicitly assumes that its executive control "allows" mind wandering whenever possible, but successfully returns its thoughts to the task at hand as soon as required. It thus fits naturally with the theory that mind wandering arises from the failure of executive resources to control one's thoughts.

Further, our model suggests that the executive control functions fail when an active enough memory competes for the model attention. The model's higher threshold for mind wandering accessing a memory (compared to normal, task-oriented access of a memory) suggests that only memories that are very recent, frequent, and/or highly related to the task or environment will be strong enough to derail one's train of thought. It also thus provides an explanation for how mind wandering content is generated, an issue which is not currently well understood (Schooler et al., 2011) nor present in other models of distraction and mind wandering (Taatgen, Katidioti, Borst, & van Vugt, 2015; van Vugt, Taatgen, Sackur, & Bastian, 2015). In van Vugt et al. (2015), for example, mind wandering is suggested to occur based on competition between "attentive" and "distracted" task control strategies, which does not extend to explain the results seen here. In our model, in contrast, memories that are highly active in memory are likely to be mind wandered about; this not only captures the results of the study we discuss here, but also ties in closely to other recent work on priming and activation in memory affecting cognitive behavior (Hiatt & Trafton, 2013, 2015; Thomson, Pyke, Trafton, & Hiatt, 2015).

Our model also expands to make several other predictions that are consistent with results generally found in mind wandering research. Another aspect of mind wandering that some have explored "mind-popping," where thoughts come to the forefront of one's mind without any conscious effort (Kvavilashvili & Mandler, 2004). Our model has a natural explanation for why that happens – the activation of a thought in memory becomes so high, through a combination of recency, frequency, priming and noise, that it pops into conscious thought regardless of whether one is currently involved in task-oriented thought.

Additionally, our model predicts that minds will wander more during low-demand tasks (McVay & Kane, 2010), and that mind wandering will occur more when one is fatigued (Smallwood et al., 2004; McVay & Kane, 2010). Fatigue, it is believed, is associated with micro lapses in cognitive processing (Gunzelmann & Gluck, 2009), resulting in no goal-oriented processing for very short periods of time. Our model predicts that, during these micro lapses, as withduring low-demand tasks that do not require much task-oriented thought, mind wandering has many more opportunities to occur. We look forward to exploring these issues in more detail in the future.

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