Thought dynamics under task demands: Evaluating the influence of task difficulty on unconstrained thought

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Abstract

As research on mind wandering has accelerated, the construct's defining features have expanded and researchers have begun to examine different dimensions of mind wandering. Recently, Christoff and colleagues have argued for the importance of investigating a hitherto neglected variety of mind wandering: "unconstrained thought," or, thought that is relatively unguided by executive-control processes. To date, with only a handful of studies investigating unconstrained thought, little is known about this intriguing type of mind wandering. Across two experiments, we examined, for the first time, whether changes in task difficulty influence rates of constrained versus unconstrained thoughts. In both experiments, participants completed either an easy (0-back) or hard (2-back) task and responded to intermittently presented thought probes that gauged thought constraint throughout the task. In Experiment 1, we found that participants completing the easy task engaged in unconstrained thoughts more frequently than those completing the difficult task. In Experiment 2, we replicated this result and further demonstrated that changes in unconstrained thought did not depend on task-relatedness (a common dimension of mind wandering). Finally, exploratory analyses showed associations between (un)constrained thought and age, verbal intelligence, and trait-level assessments of flow ('deep effortless concentration'), thereby adding further evidence to indicate a dissociation between task-relatedness and constraint. All data, analysis, manuscript, and experiment code can be found at https://osf.io/wr2vk/

Keywords: mind wandering, freely moving thoughts, task-difficulty, unconstrained thought, thought dynamics

Over the past fifteen years, mind wandering has become a prominent topic of interest (e.g., Callard et al., 2013; Christoff et al., 2016; Esterman et al., 2012; Mills et al., 2015; Schooler, 2004; Wammes et al., 2016). Initially, researchers investigated mind wandering by examining when and why people have thoughts that are unrelated to a focal task (Murray et al., 2020). However, dissatisfaction with this "task-unrelated thought" view has recently led to new theoretical frameworks of mind wandering (Seli et al., 2018; Irving, 2016; Sripada, 2018). One notable (and now highly popular) departure from the task-unrelated thought view is the recently proposed Dynamic Framework of mind wandering, which posits that mind wandering reflects relatively unconstrained thought (Christoff et al., 2016). According to this framework, constraint is defined in terms of sustained topical focus determined by either deliberate, top-down processes (i.e., cognitive control), or automatic, bottom-up processes (i.e., attentional capture by affective or sensory salience). The core thesis of the Dynamic Framework is that mind wandering is "a special case of spontaneous thought that tends to be more-deliberately constrained than dreaming, but less-deliberately constrained than creative thinking and goal-directed thought" (Christoff et al., 2016, p. 719). Unlike the task-unrelated thought view, which defines mind wandering in terms of the content of thought, the Dynamic Framework defines mind wandering in terms of how thinking unfolds over time.

Over the span of just four years, the foundational paper laying out the Dynamic Framework has become one of the most widely cited articles in the mind wandering literature, with over 516 citations already. While the field has undoubtedly been receptive to Christoff et al.'s new framework, to date, only a handful of studies have investigated unconstrained thought (Mills et al., 2018; O'Neill et al., under review; Smith A. P. et al., under review), and much is left to be learned about this intriguing phenomenon. Here, to shed some light on this aspect of mind wandering, we sought to determine whether unconstrained thought varies as a function of task difficulty.

From a methodological perspective, it is important to understand whether (and how) we can experimentally manipulate various dimensions of mind wandering, including thought constraint. Indeed, research on task-unrelated thought frequently employs task-difficulty manipulations, and these have contributed significantly to our understanding of (a) the costs of mind wandering and (b) how mind wandering responds to environmental changes (Randall et al., 2014). For instance, task-difficulty manipulations have been used to examine the effect of different rates of task-unrelated thought on reading comprehension (Forrin et al., 2019), visual processing (Smallwood et al., 2007), driving (Yanko & Spalek, 2014), and even whether people understand jokes (Zhang et al., 2020). To date, however, it is unclear whether rates of unconstrained thought are amenable to the same experimental manipulations as task-unrelated thought; yet, in the same way that the literature on task-unrelated thought has benefitted greatly from the ability to manipulate the relative frequency of task-unrelated thought, the growing literature on unconstrained thought will surely benefit from the identification of a method that can be used to indirectly manipulate thought constraint.

From a theoretical perspective, it is also important to understand the influence of task difficulty on thought constraint, since doing so could allow researchers to generate numerous testable hypotheses that could help to elucidate the nature of unconstrained thoughts. For instance, one prominent view in the mind wandering literature is that engaging in task-unrelated thought requires executive resources (Smallwood & Schooler, 2006) and, consequently, task-difficulty effects are explained in terms of the availability of resources: Difficult tasks require more executive resources, leaving fewer resources available for the maintenance of task-unrelated thoughts. Hence, increases in task-difficulty tend to produce decreases in task-unrelated thoughts.

The same effect might be observed for constrained thought. According to the Dynamic Framework (Christoff et al., 2016), constraints influence the variability of thought content and the transitions from one thought to another. Accordingly, less-constrained thought will have more variable content with less-predictable transitions between thoughts. Crucially, more-constrained thought is more strongly guided in terms of relevant task demands. This implies that constrained thought is monitored for temporal stability, whereas less-constrained thought is unmonitored (or subject to relatively lower levels of monitoring). Because monitoring is a resource-demanding process, more constrained thought should consume more executive resources. One plausible hypothesis, then, is that constraining thought—as opposed to permitting it to roam free—is a more resource-demanding process (Hypothesis A: Constraining thoughts is resource-demanding; see Figure 1). On this view, people ought to have less-constrained thoughts when resources are in low supply. Such a prediction could be empirically tested by varying task demands (and hence, the resources required to perform those tasks) and indexing rates of (un)constrained thinking during task completion: Given that easy tasks require fewer resources than hard tasks, Hypothesis A predicts higher rates of constrained thoughts (or lower rates of unconstrained thoughts) during an easy versus a hard task.

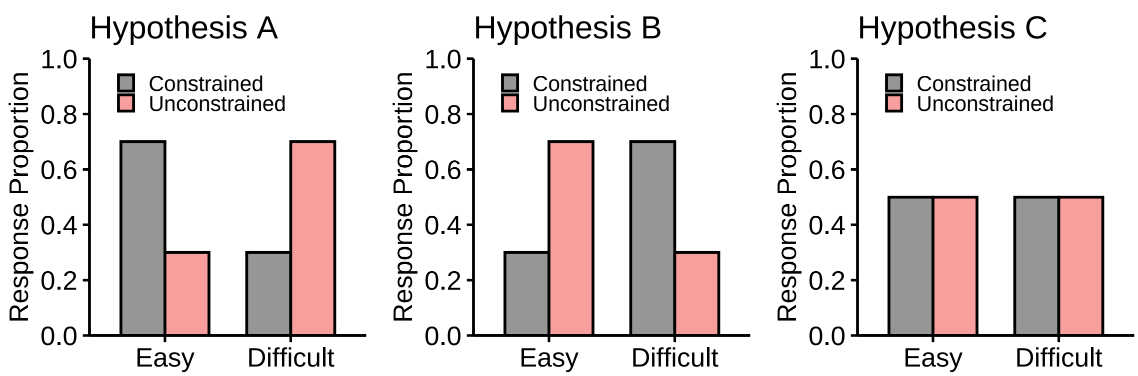

Figure 1

Predicted patterns of unconstrained thoughts as a function task difficulty. According to Hypothesis A, the act of constraining our thoughts is resource-demanding; thus, Hypothesis A predicts less constrained and more unconstrained thought when resources are reduced (i.e., in a difficult task). According to Hypothesis B, the act of engaging in unconstrained thought is resource-demanding; thus, according to this hypothesis, we should observe fewer unconstrained and more constrained thoughts when resources are reduced (i.e., in a difficult task). Finally, according to Hypothesis C, constraint/unconstraint is automatic and resource-free; hence, this hypothesis predicts no systematic change across task difficulty.

Alternatively, it also seems plausible that engaging in unconstrained thinking (i.e., exploratory thought with frequent topical shifts) may be more resource demanding than constraining them (Hypothesis B: Engaging in unconstrained thought requires executive resources; see Figure 1). Maintaining unconstrained thought over time may require suppressing salient, competing task representations and frequent switching between representations; both of which can be effortful and costly (for a review, see Koch et al., 2018). Moreover, exercising meta-control over control states, like constrained versus unconstrained states, might be more difficult when executive resources are unavailable (Dreisbach & Fröber, 2019). At the neural level, this might consist of processes that keep thoughts unconstrained by adaptively downregulating task-relevant networks to maintain mind wandering (McKiernan et al., 2006). On this basis, Hypothesis B would predict the opposite outcome of Hypothesis A: We should observe lower rates of constrained thoughts (or higher rates of unconstrained thoughts) during an easy versus a hard task.

Finally, task-difficulty manipulations might not influence thought constraint because these constraints operate independently of executive resources (Hypothesis C: Engaging constraint/unconstraint is automatic and resource-free; see Figure 1). The Dynamic Framework (Christoff et al., 2016) suggests that the constraints operating on thinking might be rooted in two different networks. One, located in frontoparietal control networks, reflects deliberate constraint, whereas the other, located in the dorsal attentional network and core regions of the default mode network, reflects automatic constraints (Christoff et al., 2016, pp. 724-25). These automatic constraints operate independently of available executive resources. As such, according to Hypothesis C, manipulations that reduce the availability of resources (e.g., task-difficulty manipulations) should have no influence on rates of thought constraint.

To the best of our knowledge, no research has yet examined the influence of task-difficulty on thought constraint. It is therefore unclear whether changes in task difficulty influence rates of thought constraint and, if so, in which direction. To shed light on this issue, here, across two experiments, we manipulated task difficulty via working-memory load using an n-back task (e.g., Baird et al., 2012; Konishi et al., 2015; Seli et al., 2018; Smallwood et al., 2011) .

In Experiment 1, participants viewed a series of numbers and were instructed to indicate whether a target was even or odd. In the "easy" task, participants were asked to indicate whether the currently presented number was even or odd (0-back), whereas in the "hard" task, they were to indicate whether the number presented two trials ago was even or odd (2-back). Periodically throughout the task, we asked participants to indicate whether their thoughts were currently freely moving or not (Mills et al., 2018). Additionally, given recent speculations (O'Neill et al., under review) that unconstrained thinking might be an instance of a "flow state" (Csikszentmihalyi, 1988; Nakamura & Csikszentmihalyi, 2014) or "deep effortless concentration" (Marty-Dugas & Smilek, 2019), for exploratory purposes, we included a trait-level assessment of flow (Marty-Dugas & Smilek, 2019) to determine whether rates of unconstrained thought were associated with this measure.

In Experiment 2, we adapted the thought probes used in Experiment 1 to include a measure of task-relatedness (i.e., "on task" or "off task") in addition to thought constraint. Constraint and task-relatedness, although seemingly dissociable (Mills et al., 2018; O'Neill et al., under review; Smith A. P. et al., under review), are closely related in that off-task thought tends to be more unconstrained and on-task thought tends to be more constrained (Mills et al., 2018; O'Neill et al., under review; Smith A. P. et al., under review). Therefore, the aims of Experiment 2 were to (a) determine whether thought constraint varies as a function of task difficulty, independently of task-relatedness, (b) further evaluate the relationship between flow and constraint, and (c) attempt to conceptually replicate the results of previous work showing dissociations of task-relatedness and thought constraint (Mills et al. 2018; O'Neill et al., under review).

Experiment 1

Method

Participants

Participants were 150 individuals (no demographic information was collected in Study 1) who completed a Human Intelligence Task (HIT) posted on Amazon Mechanical Turk (MTurk). All participants provided informed consent and were treated in accordance with guidelines approved by the ethics committee at Duke University. Participants were paid $2.00 (U.S. dollars) for completing the HIT, which lasted approximately 20 minutes. Only workers who had completed more than 5000 HITs with 98% approval rating could participate in the study.

Materials

N-back

Instructions and stimuli were displayed in the center of the screen. Stimuli were presented in a 72px black font on an off-white background. Participants completed 20 practice n-back trials, 188 experimental n-back trials, and responded to 12 thought probes. Stimuli consisted of the numbers 1 through 8 (4 even and 4 odd). Non-target stimuli were presented in black font, and target stimuli were presented in red font. Target stimuli were randomly inserted between the second and 8th trial of each block of 8 n-back trials for a total 23 targets and 165 non-targets.

In the 0-back group, participants were instructed to respond to the red digits (and not the black digits), and to indicate whether the red digits were even or odd, using the keyboard ("e" for even, "o" for odd). In the 2-back group, participants were instructed to respond to the red question mark ("?") and to indicate whether the digit presented two trials ago was even or odd using the keyboard

Thought probes

Participants were presented 12 thought probes throughout the experiment. Thought probes were randomly inserted once every 15 n-back trials, between trials 5 and 11 (on average, every 60 seconds). Thought probes consisted of a single question (Mills et al., 2018) gauging thought constraint ("The thoughts I was experiencing were freely moving: YES/NO"). Exact instructions can be found in Appendix A.

Flow state questionnaire

At the end of the experiment, participants completed a short, four-item questionnaire (adapted from Marty-Dugas, 2020) asking them to report on their thoughts during the task. Participants provided a response to each of the four items using a 5-point likert scale (strongly disagree, disagree, neutral, agree, strongly agree). The items included in this questionnaire were:

1. I was able to focus on the task without straining to pay attention
2. I seemed to reach a level of deep focus almost effortlessly
3. I got in the zone and didn't have to force myself to concentrate on the task
4. I easily paid deep attention to the task for extended periods of time.

Procedure

Participants were randomly assigned to either the 0-back or 2-back condition and were then given a general overview of the tasks and instructions on how to respond. Before moving on to the experimental trials, participants had to complete a block of 20 practice trials with 4 targets and respond correctly to 3/4 of the targets. If they failed to do so, they were required to repeat the practice trials. After completing the n-back tasks, participants completed the flow questionnaire.

Data analysis and manuscript preparation

This manuscript was prepared using R (R Core Team, 2019). A variety of notable R packages were used for data analysis (Bates et al., 2015; Fox & Weisberg, 2019; Kuznetsova et al., 2017; Singmann et al., 2019; Wickham et al., 2019; Wickham & Henry, 2019), data visualization (Fox & Weisberg, 2018; Kassambara, 2019; Wickham, 2016; Wilke, 2019), and general manuscript preparation (Aust & Barth, 2018). All data, analysis and manuscript preparation code can be found at https://osf.io/wr2vk/.

Results

We supplemented the null hypothesis tests with corresponding Bayesian analyses (Rouder et al., 2009). It is not possible to quantify the evidence for a null effect using conventional frequentist testing. A Bayes Factor, however, is a continuous measure of the relative strength of evidence and can quantify the degree to which the data are compatible with the null over the alternative hypothesis (Dienes, 2014; Rouder et al., 2009). All Bayesian analyses were performed using the R package BayesFactor and Bayes Factors (BFs) were calculated using its default settings (Morey & Rouder, 2018). $BF_1 0$ indicates evidence in favor of the alternative hypothesis whereas BF01 indicates evidence in favor of the null hypothesis. To simplify the interpretation, we report the Bayes Factor in the direction the data supports (e.g., $BF_0 1$ when there is more evidence in favor of the null over alternative hypothesis). As per previous recommendations, we refer to a BF > 3 as "moderate" and BF > 10 as "strong" evidence (Jeffreys, 1961; Rouder et al., 2009). To test for interaction effects, we contrasted the best model with the same model including/excluding the interaction effect.

N-Back performance

First, we compared sensitivity (d-prime) and bias (c) scores between n-back groups. Target discimination (d-prime) was significantly better in the 0-back versus 2-back groups, $\Delta M = 1.13$, 95% CI [0.63, 1.63], $t(148) = 4.45$, $p < .001$, $d = 0.73$, 95% CI [0.39, 1.06], $\mathrm{BF}_{10} = 1.06 \times 10^3$. Additionally, there was significantly lower response bias (c) in the 0-back versus 2-back groups, $\Delta M = -0.33$, 95% CI [-0.59, -0.07], $t(148) = -2.50$, $p = .013$, $d = -0.41$, 95% CI [-0.73, -0.08], though there was only anecdotal evidence in favor of the alternative, $\mathrm{BF}_{10} = 3.00$.

Next, we compared reaction times for accurate target responses across groups. We found no significant differences between group reaction time means, $\Delta M = -6.52$, 95% CI [-66.09, 53.05], $t(148) = -0.22$, $p = .829$, $d = -0.04$, 95% CI [-0.36, 0.29], $\mathrm{BF}_{01} = 5.57$. In addition to the standard reaction time analysis, we also performed an ex-Gaussian analysis. This approach estimates three parameters that correspond to different characteristics of the reaction time distribution: mu, sigma, and tau. Mu corresponds to the mean of the normal component of the distribution, sigma, to the standard deviation of the normal component of the distribution, and tau to the tail of the ex-Gaussian distribution (i.e., the mean and standard deviation of the exponential component of the distribution). These parameters can provide additional information regarding changes in reaction times that the estimated mean cannot provide.

Contrasting the 0-back and 2-back groups, we observed significantly larger mu in the 0-back compared to the 2-back ($\Delta M = 80.06$, 95% CI [19.50, 140.61], $t(148) = 2.61$, $p = .010$, $d = 0.43$, 95% CI [0.1, 0.75], $\mathrm{BF}_{10} = 3.88$); sigma ($\Delta M = -76.76$, 95% CI [-94.06, -59.47], $t(148) = -8.77$, $p < .001$, $d = -1.43$, 95% CI [-1.79, -1.07], $\mathrm{BF}_{10} = 1.30 \times 10^{12}$); and tau parameters ($\Delta M = -86.58$, 95% CI [$-103.47$, -69.68], $t(148) = -10.13$, $p < .001$, $d = -1.65$, 95% CI [-2.03, -1.28], $\mathrm{BF}_{10} = 3.17 \times 10^{15}$).

Counterintuitively, we found participants in the 2-back responded faster in terms of mu, but were more variable (sigma), with higher frequency and magnitude of exceedingly long reaction times (tau). The difference in mu likely reflects the foreknowledge of the correct response in the 2-back group. That is, if participants were accurately tracking whether the digit presented two trials ago was even or odd, they will know the correct response prior to the target presentation, likely speeding reaction times on those trials. Differences in sigma and tau, in contrast, likely reflect performance when participants in the 2-back condition were uncertain of the correct response due to the increase in difficulty.

The results of the n-back analysis confirm that the 2-back task was indeed more difficult than the 0-back. Participant performance was notably worse in terms of target discrimination and bias. The reaction time analyses corroborate this interpretation by showing increased variability, and higher frequency and magnitude of exceedingly long reaction times.

Thought probes

To determine whether rates of unconstrained thoughts were influenced by task difficulty, we compared rates of self-reported thought constraint across n-back groups (see Figure 2). Here, we observed significantly higher rates of freely moving thoughts in the 0-back as compared to the 2-back group, $\Delta M = 0.22$, 95% CI [0.10, 0.34], $t(148) = 3.71$, $p < .001$, $d = 0.61$, 95% CI [0.28, 0.94], with strong evidence in favor of the alternative, $\mathrm{BF}_{10} = 80.93$.

Flow questionnaire

We found no differences between mean flow state responses across n-back groups, $\Delta M = 0.04$, 95% CI $[-0.32, 0.39]$, $t(148) = 0.20$, $p = .840$, $d = 0.03$, 95% CI $[-0.29, 0.36]$, $\mathrm{BF}_{01} = 5.59$ (see 2). Given the non-normal distribution of responses, however, we also tested for difference using the Kruskal-Wallis Test, and found no differences between response distributions, $\chi^2(1) = 0.01$, $p = .922$.

Additionally, we were interested in how the response in the flow state questionnaire compared to the reported rates of unconstrained thoughts 2. Using a Pearson correlation found a significant, small to moderate, positive correlation, $r = .19$, 95% CI $[.03, .34]$, $t(148) = 2.37$, $p = .019$, $\mathrm{BF}_{10} = 2.67$, indicating some overlap between these two constructs.

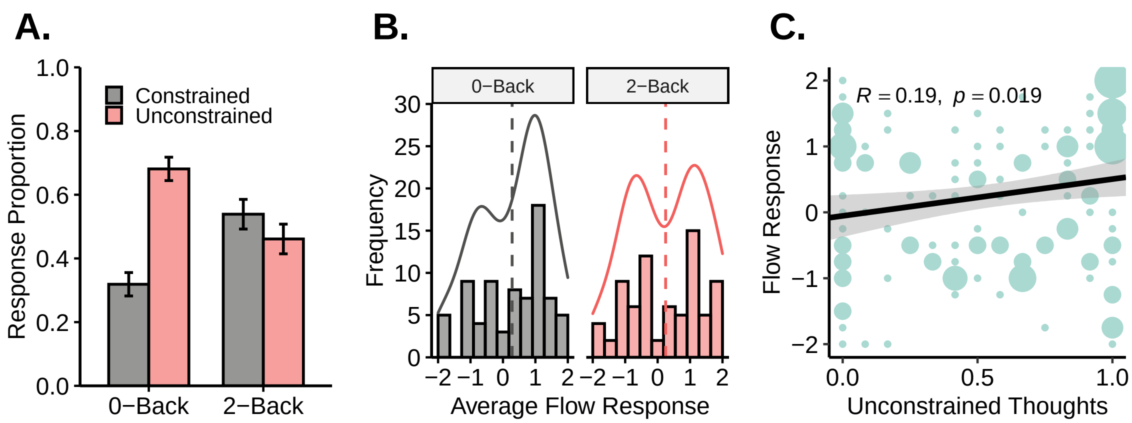

Figure 2

Results from Experiment 1. Thought constraint response proportions are plotted as a function of n-back task (A.). Frequencies of the average flow-state responses are plotted as a function of n-back task (B.), and the average flow-state responses are plotted as a function of proportions of unconstrained thought (C.). Error bars represent 95% confidence intervals around the mean.

Discussion

In Experiment 1, we examined the influence of a task-difficulty manipulation on thought constraint. To manipulate task difficulty, we used two versions of the n-back task, throughout which we periodically presented thought probes to determine whether participants' current thoughts were constrained or unconstrained. Results across performance measures confirmed that the 2-back was significantly more difficult than the 0-back. More importantly, we found that participants engaged in significantly higher rates of unconstrained thought in the easy (0-back) than the hard (2-back) task and, for both groups, the proportion of unconstrained thoughts increased across trial blocks. Consistent with Hypothesis B, this preliminary evidence suggests that unconstrained thought is indeed resource dependent . That is, when the focal task required fewer executive resources, people tended to engage in more unconstrained thought. This suggests that varying task difficulty is an effective method with which to manipulate the proportion of unconstrained thoughts.

We also compared self-reported rates of unconstrained thoughts with responses to the flow state questionnaire. Replicating a recently reported finding (Smith A. P. et al., under review), here, we found a small-to-moderate correlation between measures. Although the magnitude of the observed correlation was modest, finding some correspondence between rates of unconstrained thoughts and flow is heartening. Indeed, at face value, it seems sensible that these conceptually similar constructs should overlap to some degree. However, the relatively low correspondence suggests that the constraint dimension of mind wandering is distinct from the concept of a "flow state" (Csikszentmihalyi, 1988; Marty-Dugas & Smilek, 2019; Nakamura & Csikszentmihalyi, 2014).

One potential limitation of Experiment 1 was that we only measured general rates of (un)constrained thoughts and did not measure the task-relatedness of those thoughts. Although prior work suggests that the thought-constraint and task-relatedness dimensions of mind wandering are dissociable (e.g., Mills et al., 2018; O'Neill et al., under review; Smith A. P. et al., under review), they are not entirely independent. Mills et al. (2018), for instance, found that off-task thoughts were more likely to be unconstrained than constrained, and, conversely, that on-task thoughts were more likely to be constrained than unconstrained. Moreover, task difficulty is known to influence rates of off-task thought, with decreases in task-difficulty leading to increased rates of off-task thought (e.g., Giambra, 1989; Smallwood et al., 2011; Teasdale et al., 1995; Thomson et al., 2013). Given that (a) off-task thoughts tend to increase during easy tasks (e.g., Giambra, 1989), and (b) off-task thoughts tend to be unconstrained (e.g., Mills et al. 2018), one possibility is that the task-difficulty manipulation used in Experiment 1 might have selectively increased the overall rate of off-task thoughts (rather than directly influencing thought constraint),which could have incidentally resulted in higher rates of unconstrained thought during the easy (0-back) compared to the hard (2-back) task.

Another potential limitation of Experiment 1 was that, because we did not index the task-relatedness of participants' thoughts, we may not have adequately tested the hypothesis that unconstrained thoughts are positively associated with flow. It could, for instance, be that the hypothesized positive relation between flow and unconstrained thoughts is qualified by the task-relatedness of thoughts. Along these lines, in recent work, O'Neill et al. (under review) observed the surprising finding of relatively high rates of probe responses that were both on-task and unconstrained. This finding is surprising given that unconstrained thought has been argued to reflect thoughts that are antithetical to goal-directed, on-task thoughts (Christoff et al., 2016); thus, on-task thoughts should be constrained, rather than unconstrained. To explain this finding, O'Neill et al. proposed that the Mills et al. (2018) constraint probes may not measure topical shifts, but instead the effortfulness of thoughts (where unconstrained thoughts are those that feel relatively effortless). Indeed, if one is on-task and engaging in unconstrained thoughts, it would appear that such thoughts could not involve topical-shifts (else they would not be on-task), so they may instead consist of thoughts that reflect a goal-directed flow state (Csikszentmihalyi, 1988; Nakamura & Csikszentmihalyi, 2014) or a state of "deep effortless concentration" (Marty-Dugas & Smilek, 2019). At the same time, because flow states reflect deep effortless concentration on a focal task, one might not expect off-task thoughts (whether constrained or unconstrained) to be positively associated with flow. Thus, if O'Neill et al.'s hypothesis is correct, we should expect to observe a significant positive correlation with flow only when examining rates of on-task, unconstrained thoughts (and perhaps negative correlations with flow when examining off-task thoughts, whether constrained or unconstrained).

Experiment 2

Having established that rates of unconstrained thought can be manipulated via changes in task difficulty, the primary aim of Experiment 2 was to determine whether variations in task difficulty influence rates of thought constraint for both on- and off-task thought. As noted above, research has found that (a) decreases in task difficulty lead to increased rates of off-task thought (e.g., Giambra, 1989; Smallwood et al., 2011; Teasdale et al., 1995; Thomson, Besner, & Smilek, 2013), and (b) whereas off-task thoughts are more likely to be unconstrained than on-task thoughts, on-task thoughts are more likely to be constrained than off-task thoughts (Mills et al., 2018; Smith et al., under review). Thus, in Experiment 2, we sought to determine how thought-probe responses varied under a task-difficulty manipulation when both task-relatedness and thought constraint were measured. A secondary aim of Experiment 2 was to better evaluate the relationship between constraint and flow by testing O'Neill et al.'s (under review) hypothesis that the concept of a "flow state" or "deep effortless concentration" is closely associated with unconstrained on-task thoughts, and not unconstrained or off-task thoughts in general. The third and final aim of Experiment 2 was to conceptually replicate the work of Mills et al. (2018) using a laboratory task. Mills et al. used a time-consuming and costly experience-sampling procedure for which they examined task-relatedness and thought constrained in daily life, via probes sent to participants' smartphones. Methodologically, it is important to know whether a simple, online task would produce the same pattern of thought-probe responses as the Mills et al. experience-sampling procedure. If so, this would suggest that researchers who are interested in testing hypotheses about thought constraint and task-relatedness could forgo the lengthy experience-sampling procedure and instead use the much simpler online task.

We again used the n-back tasks to manipulate task difficulty. Extending our design in Experiment 1, here we included thought probes that gauged both thought constraint (constrained, unconstrained) and task-relatedness (on-task, off-task). We also included a demographics survey, as well as the Wordsum test (a brief vocabulary test that correlates well with full-scale measures of intelligence; Huang & Hauser, 1998). We included these measures to explore how rates of thought constraint might be related to age (Maillet & Schacter, 2016) and/or verbal intelligence (e.g., Mrazek et al., 2012), respectively. We ran two samples, both pre-registered prior to data collection (Sample 1: https://osf.io/2djqf; Sample 2: https://osf.io/guq7j).

Because no other studies have examined on- and off-task (un)constrained thought under task-difficulty manipulations, it was not possible to conduct an a priori power analysis. Thus, we decided to collect data from a relatively large sample ($N = 150$, 75 per group), with the intention of attempting to replicate any significant findings we observed. In Sample 1, we found a non-significant three-way interaction between n-back, thought constraint, and task relatedness ($p > .05$) and a significant two-way interaction between thought constraint and n-back condition ($p = .01$). To improve our confidence in this result, we collected an additional 300 participants (150 per group) to augment those from our initial sample. Below, we report the results of an analysis combining data from both samples; however, individual sample analyses can be found in the supplementary material (critically, both samples converged on the same general conclusions). As in Experiment 1, we supplemented the null hypothesis tests with corresponding Bayesian analyses.

Method

Participants

Sample 1 consisted of 150 individuals (43.7% Female, mean age = 40 ($sd = 12.5$)) who completed a HIT on Amazon Mechanical Turk; Sample 2 consisted of 300 individuals (46.8% Female, mean age = 40.2 ($sd = 12.5$)) . All participants provided informed consent and were treated in accordance with guidelines approved by the ethics committee at Duke University. Participants were paid $2.50 (U.S. dollars) for completing the HIT, which lasted approximately 25 minutes.

Materials

N-back

The n-back tasks were identical to Experiment 1.

Thought probes

Instructions and stimuli were identical to Experiment 1. However, in addition to asking participants to report whether their thoughts were freely moving or not (identical to Experiment 1), we also asked whether their current thoughts were on- or off-task ("Just prior to seeing this screen, I was: (a) on-task (b) thinking task-unrelated thoughts"). Verbatim instructions are reported in Appendix B.

Wordsum test

The Wordsum test (Huang & Hauser, 1998) is a verbal intelligence test in which participants are asked to identify which of five words comes closes in meaning to a target word. For example, one of the target words is *accustom* and the five options are *disappoint*, *customary*, *encounter*, *get used to*, or *business*. The traditional version consists of 10 target words. In the version presented here, we included two additional target words, *audacious* (options: *smart*, *daring*, *brave*, *loud*, or *outgoing*) and *encumber* (options: *oppress*, *gather*, *impede*, *press*, or *encompass*). As such, it is commonly used as a proxy for intelligence in many psychological, sociological, and political science studies (e.g., Malhotra et al., 2007; Pennycook et al., 2012) and included in the 16 General Social Surveys (Davies & Smith, 1994).

Flow state and demographics questionnaires

Following the Wordsum, participants completed the same flow state questionnaire completed in Experiment 1, and an optional demographics questionnaire.

Procedure

The procedure was identical to Experiment 1. After the n-back task participants completed the flow questionnaire, followed by the Wordsum, then the demographics survey.

Results

N-Back performance

Target discimination (d-prime) was significantly better in the 0-back versus 2-back groups, $\Delta M = 0.67$, 95% CI [0.41, 0.93], $t(448) = 5.09$, $p < .001$, $d = 0.48$, 95% CI [0.29, 0.67], $\mathrm{BF}_{10} = 2.22 \times 10^4$. Additionally, there was significantly lower response bias (c) in the 0-back versus 2-back groups, $\Delta M = -0.42$, 95% CI [-0.54, -0.30], $t(448) = -7.00$, $p < .001$, $d = -0.66$, 95% CI [-0.85, -0.47], $\mathrm{BF}_{10} = 7.65 \times 10^8$. We found no significant differences between group reaction time means, $\Delta M = 8.16$, 95% CI [-25.96, 42.28], $t(448) = 0.47$, $p = .639$, $d = 0.04$, 95% CI [-0.14, 0.23], $\mathrm{BF}_{01} = 8.59$. However, we did observe significant differences in the mu ($\Delta M = 78.02$, 95% CI [42.50, 113.55], $t(448) = 4.32$, $p < .001$, $d = 0.41$, 95% CI [0.22, 0.59], $\mathrm{BF}_{10} = 749.84$), sigma ($\Delta M = -69.03$, 95% CI [$-79.18$, -58.89], $t(448) = -13.37$, $p < .001$, $d = -1.26$, 95% CI [-1.46, -1.06], $\mathrm{BF}_{10} = 1.44 \times 10^{31}$), and tau parameters ($\Delta M = -69.87$, 95% CI [$-80.26$, -59.47], $t(448) = -13.21$, $p < .001$, $d = -1.25$, 95% CI [-1.45, -1.04], $\mathrm{BF}_{10} = 3.10 \times 10^{30}$). These results are consistent with Experiment 1: the 2-back group were quicker in terms of mu, but showed greater variability sigma and a longer tail tau. The differences in mu again likely reflect the foreknowledge of the correct response prior to the target stimulus, whereas the differences in sigma and tau likely reflect the increase in general task difficulty.

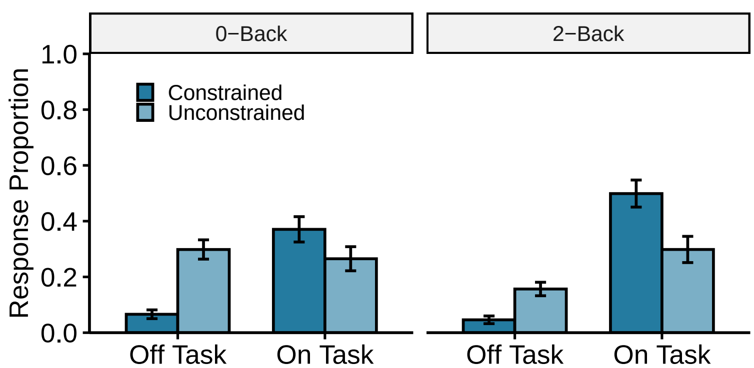

Figure 3

Results of the thought-probe trials from Experiment 2 plotted as a function of n-back, task relatedness and constraint. Error bars represent 95% confidence intervals around the mean. We found no significant three-way interaction (p > .05) and strong evidence against including the three-way interaction in the model (BF = 15.65).

Thought Probes

We analyzed response proportions using 2 x 2 x 2 mixed analysis of variance (ANOVA) with task relatedness (on versus off task) and constraint (constrained versus unconstrained) as within-subjects factors and n-back task (0-back versus 2-back) as the between-subjects factors (see Figure 3). It is also worth noting that the dependent measure in our design is ipsative (i.e., proportions sum to 1) and may violate assumptions typically required for an Analysis of Variance. However, the Analysis of Variance has been shown to be robust against violations of assumptions resulting from ipsativity (Greer & Dunlap, 1997).

The primary question of interest was whether changes in constraint across n-back conditions depended on task relatedness (see Figure 3). To that end, we first looked at the three-way interaction between n-back, constraint, and task-relatedness and found no significant interaction effect, $F(1, 448) = 0.17$, $MSE = 0.12$, $p = .683$, $\hat{\eta}^2_p < .001$, 90% CI [0, 0.01]. Moreover, according to the Bayesian analyses, the model containing all main effects and all two-way interactions ($\mathrm{BF}_{10} = 3.74 \times 10^{83}$) was preferred over the full model including the three-way interaction by a factor of , $\mathrm{BF}_{01} = 7.53$. The evidence *against* a three-way interaction provides evidence that any changes in constraint across n-back conditions *did not* depend on whether the thoughts were on or off task. Therefore, we continued to analyze and interpret each of the following two-way interactions.

Thought constraint and N-back condition

Next, we examined whether constraint varied across n-back groups and found a significant interaction between n-back and constraint, $F(1, 448) = 10.43$, $MSE = 0.13$, $p = .001$, $\hat{\eta}^2_p = .023$, 90% CI [0.01, 0.05], with strong evidence in favor of including the interaction effect, $\mathrm{BF}_{10} = 152.68$. Following up the interaction, we found off higher rates of unconstrained thought in the 0- versus 2-back condition $\Delta M = 0.11$, 95% CI [0.04, 0.17], $t(448) = 3.23$, $p = .001$, $d = 0.3$, 95% CI [0.12, 0.49], $\mathrm{BF}_{10} = 15.65$ replicating the results from Experiment 1.

N-back condition and task-relatedness

The two-way interaction between n-back task and task relatedness was significant, $F(1, 448) = 46.31$, $MSE = 0.06$, $p < .001$, $\hat{\eta}^2_p = .094$, 90% CI [0.05, 0.14], with strong evidence in favor of including this interaction effect, $\mathrm{BF}_{10} = 1.03 \times 10^7$. In a follow-up analysis, we found the proportion off task thoughts was significantly lower in the 2-back versus 0-back condition, $\Delta M = -0.16$, 95% CI [-0.21, -0.11], $t(448) = -6.81$, $p < .001$, $d = -0.64$, 95% CI [-0.83, -0.45], $\mathrm{BF}_{10} = 2.30 \times 10^8$.

Thought constraint and task-relatedness

Finally, the two-way interaction between task relatedness and constraint was also significant, $F(1, 448) = 98.51$, $MSE = 0.12$, $p < .001$, $\hat{\eta}^2_p = .180$, 90% CI [0.13, 0.23], with strong evidence in favor of including the interaction effect, $\mathrm{BF}_{10} = 2.43 \times 10^{31}$. Following up the interaction, as in Mills et al. (2018), we found that off-task thoughts were more likely to be unconstrained than constrained, $\Delta M = -0.17$, 95% CI [-0.20, -0.15], $t(898) = -13.82$, $p < .001$, $d = -0.92$, 95% CI [-1.08, -0.77], $\mathrm{BF}_{10} = 1.88 \times 10^{33}$, and on task thoughts were more likely to be constrained than unconstrained, $\Delta M = 0.15$, 95% CI [0.11, 0.20], $t(898) = 6.48$, $p < .001$, $d = 0.43$, 95% CI [0.25, 0.61], $\mathrm{BF}_{10} = 7.22 \times 10^3$.

Summary

To summarize, we found evidence against a three-way interaction between n-back task, task-relatedness, and constraint. The lack of three-way interaction is important in that it provides evidence that changes in constraint across n-back conditions did not vary as a function of task-relatedness (see Figure 3). Additionally, we found higher rates of unconstrained thought in the 0- versus 2-back condition, replicating the results from Experiment 1 (see Figure 4C). We also found higher rates of off-task thought and lower rates of on-task thought in the 0- versus 2-back conditions (see Figure 4A); And found off-task thoughts were more often unconstrained than constrained, and on-task thoughts were more often constrained than unconstrained (see Figure 4B).

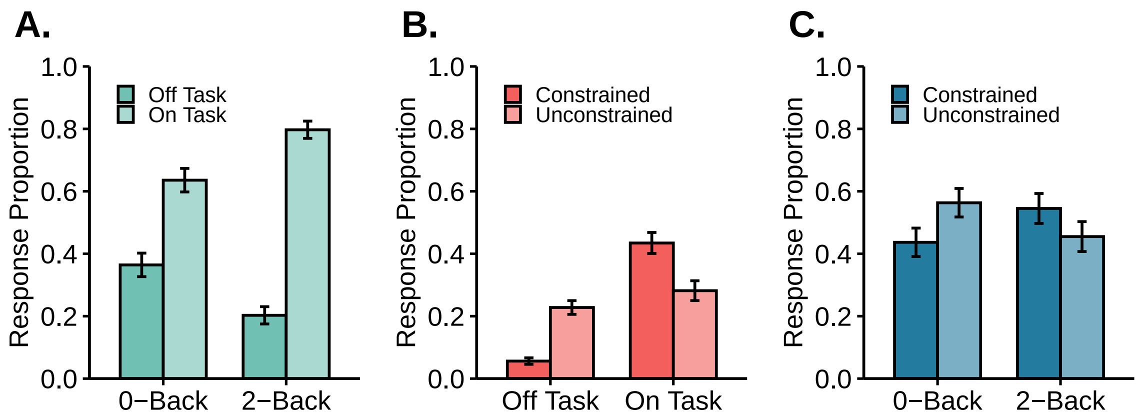

Figure 4

Results of the thought-probe trials from Experiment 2. Plotted are the two-way interactions between task relatedness and n-back (A.), task relatedness and constraint (B.), and constraint and n-back (C.). Error bars represent 95% confidence intervals around the mean. All two-way interactions were significant (ps < .05) with overwhelming evidence to include the two-way interaction in each of the models (BFs > 150).

Flow Questionnaire

We analyzed the flow state questionnaire responses and compared them to the thought probe responses e2twoway. We found no significant difference between mean flow state responses across n-back groups using a t-test, $\Delta M = 0.12$, 95% CI $[-0.08, 0.31]$, $t(448) = 1.19$, $p = .235$, $d = 0.11$, 95% CI $[-0.07, 0.3]$ and no significant difference using the Kruskal-Wallis Test, $\chi^2(1) = 1.89$, $p = .169$.

We were also interested in how the response in the flow state questionnaire compared to each of the response types. We compared each using a Pearson correlation and found a small, non-significant correlation between rates of constrained on-task thought and flow responses, $r = .08$, 95% CI $[-.01, .17]$, $t(448) = 1.66$, $p = .099$, $\mathrm{BF}_{01} = 2.36$; a significant positive correlation between unconstrained on-task thought and flow responses, $r = .21$, 95% CI $[.12, .29]$, $t(448) = 4.50$, $p < .001$, $\mathrm{BF}_{10} = 1.92 \times 10^3$; a significant negative correlation between constrained off-task thought and flow responses, $r = -.21$, 95% CI $[-.30, -.12]$, $t(448) = -4.54$, $p < .001$, $\mathrm{BF}_{10} = 2.32 \times 10^3$; and a significant negative correlation between unconstrained thought and flow responses, $r = -.32$, 95% CI $[-.40, -.23]$, $t(448) = -7.13$, $p < .001$, $\mathrm{BF}_{10} = 2.35 \times 10^9$.

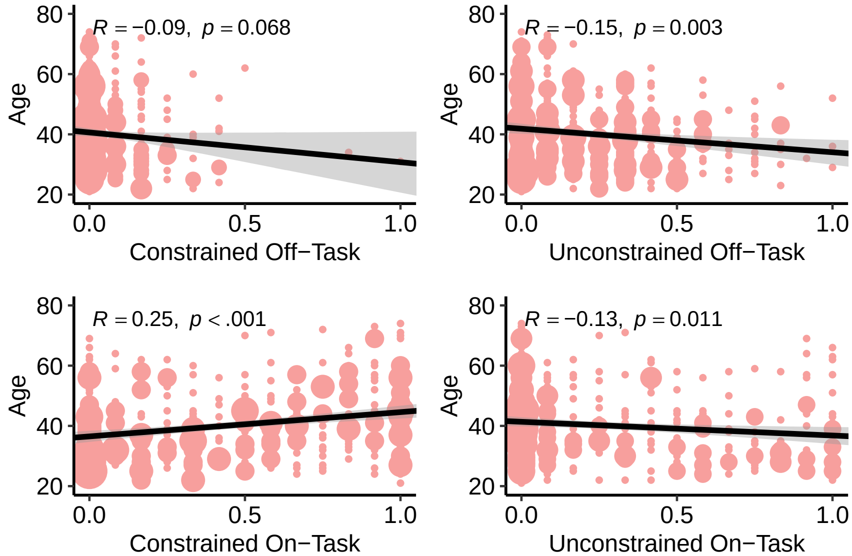

Figure 5

Results from Experiment 2 (both samples). Age is plotted as a function of thought probe response proportions.

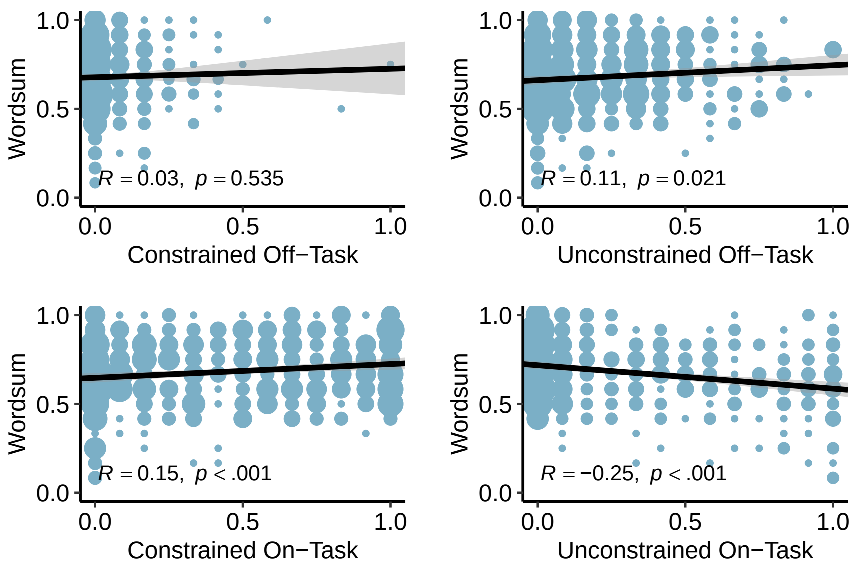

Figure 6

Results from Experiment 2 (both samples). Wordsum scores are plotted as a function of thought probe response proportions.

Exploratory Analyses

Thought probe responses and age

First, we correlated age with each of the thought-probe response proportions (see Figure 5). Out of the 450 participants, 377 completed the optional demographics survey. We found that age was not significantly correlated with constrained off-task thought, $r = -.09$, 95% CI [−.19, .01], $t(375) = -1.83$, $p = .068$, $\mathrm{BF}_{01} = 1.60$, but was negatively correlated with unconstrained off-task thought, $r = -.15$, 95% CI [−.25, −.05], $t(375) = -3.00$, $p = .003$, $\mathrm{BF}_{10} = 9.63$. Additionally, age was positively correlated with constrained on-task thought, $r = .25$, 95% CI [.15, .34], $t(375) = 4.96$, $p < .001$, $\mathrm{BF}_{10} = 1.51 \times 10^4$ and negatively correlated with unconstrained on-task thought, $r = -.13$, 95% CI [−.23, −.03], $t(375) = -2.55$, $p = .011$, $\mathrm{BF}_{10} = 2.86$.

Thought probe responses and verbal intelligence

Next, we correlated Wordsum test accuracy scores with the thought probe response proportions (see Figure 6). Here, we found that Wordsum scores did not significantly correlate with either constrained off-task thought, $r = .03$, 95% CI [−.06, .12], $t(448) = 0.62$, $p = .535$, $\mathrm{BF}_{01} = 7.50$. However, it did positively correlate with constrained on-task thought, $r = .15$, 95% CI [.06, .24], $t(448) = 3.27$, $p = .001$, $\mathrm{BF}_{10} = 20.13$ and negatively correlate with unconstrained on-task thought, $r = -.25$, 95% CI [−.33, −.16], $t(448) = -5.37$, $p < .001$, $\mathrm{BF}_{10} = 1.10 \times 10^5$, and unconstrained off-task thought, $r = .11$, 95% CI [.02, .20], $t(448) = 2.32$, $p = .021$, $\mathrm{BF}_{10} = 1.53$.

Using the subset of participants who completed the demographics questionnaire (N = 377), we tested whether the previous associations were present after controlling for age. The results of each linear regression model produced the same directional effects as the previous analyses: We found Wordsum scores were not associated with constrained off-task thought $b = -0.03$, 95% CI [−0.19, 0.13], $t(374) = -0.40$, $p = .688$, but they were positively associated with constrained on-task thought $b = 0.05$, 95% CI [0.00, 0.11], $t(374) = 2.10$, $p = .036$, negatively associated with unconstrained on-task thought $b = 0.08$, 95% CI [0.00, 0.16], $t(374) = 2.08$, $p = .038$, and positively associated with unconstrained off-task thought $b = -0.10$, 95% CI [−0.15, −0.04], $t(374) = -3.53$, $p < .001$.

Flow and age

Next, we examined the relationship between flow state responses and age (see Figure 6) and found no significant correlation, $r = .00$, 95% CI [−.10, .10], $t(375) = -0.03$, $p = .976$, with moderate evidence in favor of the null, $\mathrm{BF}_{10} = 8.31$.

Flow and verbal intelligence

Finally, we examined the relationship between flow state responses and Wordsum test accuracy scores (see Figure 6). First we used a Pearson correlation and found a significant negative association, $r = -.11$, 95% CI [−.20, −.02], $t(448) = -2.38$, $p = .018$. Using a linear regression model controlling for age, we also found a significant negative association, $b = -0.62$, 95% CI [−1.19, −0.04], $t(374) = -2.11$, $p = .035$.

Discussion

In Experiment 2, we examined the influence of a task-difficulty manipulation on thought-probe responses when both thought constraint and task-relatedness were measured. To manipulate task difficulty, we used two versions of the n-back task and periodically presented thought probes to determine whether participants' thoughts were constrained or unconstrained. Results across performance measures confirmed that the 2-back was significantly more difficult than the 0-back.

More importantly, we found that participants engaged in significantly higher rates of unconstrained thought in the easy versus the hard task. The evidence against a three-way interaction suggests that the manipulation of constraint did not depend on task-relatedness. Replicating prior work, we also found lower rates of off-task thought in the hard task as compared to the easy task (e.g., Giambra, 1989; Smallwood et al., 2011; Teasdale et al., 1995; Thomson, Besner, & Smilek, 2013). Similarly, we found that, whereas off-task thoughts were more likely to be unconstrained than constrained, on-task thoughts were more likely to be constrained (Mills et al., 2018; Smith et al., under review). Given the association between constraint and task-relatedness and that task difficulty manipulations produced additive effects (i.e., increasing both task-unrelated thought and unconstrained thought independently), we suggest that future work using variations in task difficulty to manipulate thought constraint should also measure task-relatedness to determine how much of the change is due to a shift in off-task thought.

In Experiment 1 we found a small positive association between rates of unconstrained thought and trait-level measures of flow. However, in Experiment 2 we found this relationship did depend on task-relatedness: Whereas unconstrained on-task thought was positively correlated with flow, unconstrained on-task thought was negatively correlated with flow. Again, this points to the importance of measuring both the constraint and task-relatedness dimensions. The overall pattern of results suggests that flow states (Csikszentmihalyi, 1988; Marty-Dugas & Smilek, 2019; Nakamura & Csikszentmihalyi, 2014) are not identical to unconstrained thought. However, flow might reflect a particular kind of on-task unconstrained thought which fits well with the idea that a flow state is effortless concentration (Marty-Dugas & Smilek, 2019).

Turning to our exploratory analyses, we found that age was positively associated with constrained on-task thought, but negatively associated with unconstrained off-task thought. This aligns with prior work showing rates of task-unrelated thought tends to decrease with age (e.g., Jackson & Balota, 2012; Seli et al., 2020). It also suggests that constrained on-task reports may be capturing traditional measures of task-related thought, and that unconstrained off-task may be capturing traditional measures of task-unrelated thoughts. However, we also found that age was negatively associated with unconstrained on-task thought. This result is particularly interesting as it suggests that unconstrained on-task thought is more like mind wandering than focused on-task thought and is consistent with the view that constraint and task-relatedness are dissociable (e.g., Mills et al., 2018; O'Neill et al., under review).

We also examined the relationship between verbal intelligence, as indexed by the WordSum scores, and thought probe responses. To our knowledge, there is only one similar study that used the WordSum test and they found no association between rates of task-unrelated thought and verbal intelligence (Phillips et al., 2016). However, more generally, task-unrelated thought (i.e., mind wandering) has been shown to be negatively associated with measures of general intelligence (Mrazek et al., 2012). In this regard, our result is mixed. On the one hand, constrained on task thought was positively associated with verbal intelligence. This is consistent with the prior claim. On the other hand, we found a small, positive association between unconstrained off-task thought and verbal intelligence and a negative association between unconstrained on-task thought and verbal intelligence. Again, this suggests that unconstrained on-task thought more closely resembles traditional conceptualizations of mind wandering than it does focused, on task thought.

Finally, we examined the relationship between flow state responses, age, and verbal intelligence. Previous work has indicated that the tendency to experience flow may actually increase across the lifespan (Marty-Dugas & Smilek, 2019; Ullén et al., 2012). However, despite a large sample and wide distribution of ages, here we find no association between age and flow state responses. Looking at verbal intelligence we find a small negative association between flow state responses and WordSum scores. Prior work has found small but inconsistent associations between intelligence and flow state using much larger samples and concluded that they were essentially unrelated (Ullén et al., 2012).

General Discussion

The primary question addressed across these two experiments was whether manipulating task difficulty would influence thought constraint (Christoff et al., 2016; Mills et al., 2018; Smith et al., under review). From the Dynamic Framework's perspective, we hypothesized that both unconstrained and constrained thought could be more or less resource demanding depending on the underlying assumptions. These hypotheses resulted in diverging predictions about how task difficulty should influence the rate of (un)constrained thought (see Figure 1 for a summary). In Experiment 1, we found lower rates of unconstrained thought in the more difficult 2-back condition as compared to the 0-back condition, suggesting that constraint can be manipulated by varying task difficulty and that engaging in unconstrained thoughts is a resource-demanding process. In Experiment 2, we replicated the finding of lower rates of unconstrained thought in the more difficult condition, again providing evidence that thought constraint can be manipulated via a task-difficulty manipulation, and that unconstrained thoughts require executive resources. More importantly, in Experiment 2, we also determined that this manipulation did not depend on task-relatedness. Furthermore, we replicated prior work that (a) participants engage in more off-task thought during easier tasks (e.g., Giambra, 1989; Smallwood et al., 2011; Teasdale et al., 1995; Thomson, Besner, & Smilek, 2013), and (b) off-task thought was more likely to be unconstrained than constrained and on-task thought was more likely to be constrained than unconstrained (Mills et al., 2018; O'Neill et al., under review; Smith et al., under review). Together, these results were most consistent with Hypothesis B (i.e., engaging in unconstrained thought requires executive resources), and suggest that unconstrained thought is indeed resource dependent: When the focal task is demanding, and resources are restricted, people tend to engage in less unconstrained thought and more constrained thought.

Given the current results, future work is needed to further determine the parallels (and distinctions) between task-unrelated thought and unconstrained thought. For instance, Xu and Metcalf (2016) found that the influence of task-difficulty on task-unrelated thought is non-linear, following a u-shaped function; When a task becomes too difficulty people start to engage in more task-unrelated thought. We might expect a similar pattern of results with unconstrained thought had we used a more parametric variation of task difficulty. Similarly, much work has established an association between working memory capacity and task-unrelated thought (e.g., McVay & Kane, 2009, 2012). Our finding that unconstrained thought may be resource-dependent suggests a similar relationship with working memory capacity. Finally, and more practically, we might consider the clinical implications of maladaptive thought constraint. Attention deficit hyperactivity disorder (ADHD), for instance, bears a striking resemblance to current conceptualizations of unconstrained thought (e.g., Christoff, et al., 2016). It might be the case that over-engaging in unconstrained thought, because of its resource-dependency, incurs performance costs in focal tasks; All fruitful avenues for future work.

At the methodological level, the results of the present study are rather promising for future investigations on unconstrained thought because they demonstrate a method with which to indirectly influence rates of unconstrained thought. This could be useful for future work exploring the costs and benefits of unconstrained thought. For instance, experimental manipulations increasing unconstrained thought would surely be beneficial for examining whether unconstrained thought benefits creative idea generation (Baird et al., 2012), results in increases in topical shifts, or improves boredom management. Conversely, manipulating unconstrained thought would be useful for examining the negative consequences of thought constraint, such as rumination or fixation (Christoff, 2016). Just as the mind wandering literature has benefited from experimental manipulations of task-unrelated thought, our novel finding that task difficulty can influence unconstrained thought, will surely benefit the growing literature on unconstrained thought.

However, our study also identifies two caveats in using our experimental manipulations. First, although we clearly established that task difficulty can be used to manipulate rates of thought constraint, the results of Experiment 2 demonstrate the need to supplement assessments of constraint with measures of task-relatedness. Since both task-relatedness and thought constraint are influenced by task difficulty, it is possible that changes in task relatedness could appear as changes in constraint. Second, our distribution of thought-probe responses was similar to, but not identical with, Mills et al.'s (2018), who used experience sampling. The main discrepancy concerns rates of constrained off-task thought. Whereas Mills et al. found ~20% of reports to be constrained and off-task, participants in our task only reported ~5%. Therefore, our laboratory task should be sufficient for those interested in the other thought-probe responses, but inappropriate if one were interested in reports of constrained off-task thought.

Another limitation of our study is that we did not control for or measure motivation. By manipulating task difficulty, we presumably restricted the amount of attentional resources available in the difficult versus easy conditions, and concluded—on that basis—that the restriction of resources influenced thought dynamics. However, motivation has also been shown to be a key moderator of thought content and dynamics (Brosowsky et al., in press; Giambra, 1989; Smallwood et al., 2011; Teasdale et al., 1995; Thomson et al., 2013). A. C. Smith et al. (under review), for instance, found that increasing motivation increased constrained on-task thought and decreased unconstrained off-task thought. One possibility, then, is that increasing task demands decreases motivation, which consequently influences rates of (un)constrained thought. Notably, this alternative explanation would also apply to task-difficulty manipulations of task-unrelated thought (e.g., Giambra, 1989; Smallwood et al., 2011; Teasdale et al., 1995; Thomson, Besner, & Smilek, 2013) since motivation is also known to influence rates of task-unrelated thought (e.g., Brosowsky et al., 2020; Seli, et al., 2019). In any case, further work is needed to tease apart the potentially interactive effects of task demands and motivation on both task-unrelated thought and (un)constrained thought.

Finally, we reported a number of exploratory analyses examining the relationships between thought probe responses and flow, age, and verbal intelligence. Of those results, there were three key takeaways. First, lending further support to recent research (Mills et al., 2018; O'Neill et al., under review), thought constraint and task-relatedness do not appear to be redundant. That is, relationships between thought-probe responses and other measures did not converge consistently along one dimension or the other as one would expect if they were redundant. Second, consistent with O'Neill et al.'s (under review) proposal, we found that unconstrained on-task thought was associated with flow. Although in Experiment 1, we found a small positive relationship between unconstrained thought and flow (similar to Smith A. P. et al., under review), in Experiment 2, we found flow state responses were positively associated with unconstrained on-task thought and negatively associated with unconstrained off-task thought. This result, though preliminary, is promising, as it suggests there is some relationship between unconstrained thought and the concept of a "flow state" (Csikszentmihalyi, 1988; Nakamura & Csikszentmihalyi, 2014) or "deep effortless concentration" (Marty-Dugas & Smilek, 2019). Third, and finally, unconstrained thought seems to behave differently when associated with on task versus off task thought. This is evidenced by the differential relationship between age, verbal intelligence, and flow measures. These differential patterns suggest that although unconstrained thought is always resource demanding, the role that it may play may differ depending on whether thoughts are currently on or off task. This distinction might be critical for understanding the costs and benefits of engaging in (un)constrained thought.

Concluding Remarks

From a methodological perspective, we have established that task difficulty can be used to effectively manipulate rates of thought constraint and outlined some important limitations regarding this manipulation. In the same way that the literature on task-unrelated thought has benefitted greatly from the ability to manipulate the relative frequency of task-unrelated thought, the growing literature on unconstrained thought will surely benefit from our novel finding that task difficulty can indirectly manipulate constraint in a brief online task. From a theoretical perspective, our results provide novel evidence that unconstrained thought is resource-dependent: When resources are limited, participants engage in less unconstrained thought. Moreover, we found additional evidence that constraint and task-unrelatedness are dissociable dimensions of mind wandering, and we observed a positive association between flow states and on-task constrained thought which helps to clarify prior reports of associations between unconstrained thought and flow, but warrants further investigation. These important theoretical contributions further refine thought constraint as a construct within the Dynamic Framework and narrow the candidate processes underlying (un)constrained thought.

References

Aust, F., & Barth, M. (2018). *papaja: Create APA manuscripts with R Markdown.* https://github.com/crsh/papaja

Baird, B., Smallwood, J., Mrazek, M. D., Kam, J. W., Franklin, M. S., & Schooler, J. W. (2012). Inspired by distraction: Mind wandering facilitates creative incubation. *Psychological Science*, *23*(10), 1117–1122.

Bates, D., Mächler, M., Bolker, B., & Walker, S. (2015). Fitting linear mixed-effects models using lme4. *Journal of Statistical Software*, *67*(1), 1–48. https://doi.org/10.18637/jss.v067.i01

Brosowsky, N. P., Degutis, J., Esterman, M., Smilek, D., & Seli, P. (in press). Mind wandering, motivation, and task performance over time. In *Psychology of Consciousness: Theory Research, and Practice*.

Callard, F., Smallwood, J., Golchert, J., & Margulies, D. S. (2013). The era of the wandering mind? Twenty-first century research on self-generated mental activity. *Frontiers in Psychology*, *4*, 891.

Christoff, K., Irving, Z. C., Fox, K. C., Spreng, R. N., & Andrews-Hanna, J. R. (2016). Mind-wandering as spontaneous thought: A dynamic framework. *Nature Reviews Neuroscience*, *17*(11), 718.

Csikszentmihalyi, M. (1988). *The flow experience and its significance for human psychology.*

Dienes, Z. (2014). Using Bayes to get the most out of non-significant results. *Frontiers in Psychology*, *5*, 781.

Dreisbach, G., & Fröber, K. (2019). On how to be flexible (or not): Modulation of the stability-flexibility balance. *Current Directions in Psychological Science*, *28*(1), 3–9.

Esterman, M., Noonan, S. K., Rosenberg, M., & DeGutis, J. (2012). In the zone or zoning out? Tracking behavioral and neural fluctuations during sustained attention. *Cerebral Cortex*, *23*(11), 2712–2723.

Forrin, N. D., Risko, E. F., & Smilek, D. (2019). On the relation between reading difficulty and mind-wandering: A section-length account. *Psychological Research*, *83*(3), 485–497.

Fox, J., & Weisberg, S. (2018). Visualizing fit and lack of fit in complex regression models with predictor effect plots and partial residuals. *Journal of Statistical Software*, *87*(9), 1–27. https://doi.org/10.18637/jss.v087.i09

Fox, J., & Weisberg, S. (2019). *An R companion to applied regression* (Third). Sage. https://socialsciences.mcmaster.ca/jfox/Books/Companion/

Giambra, L. M. (1989). Task-unrelated thought frequency as a function of age: A laboratory study. *Psychology and Aging*, *4*(2), 136.

Greer, T., & Dunlap, W. P. (1997). Analysis of variance with ipsative measures. *Psychological Methods*, *2*(2), 200.

Huang, M.-H., & Hauser, R. (1998). Trends in Black-White test-score differentials: II. The WORDSUM vocabulary test. In U. Neisser (Ed.), *The rising curve: Long-term gains in IQ and related measures.* American Psychological Association.

Jackson, J. D., & Balota, D. A. (2012). Mind-wandering in younger and older adults: Converging evidence from the sustained attention to response task and reading for comprehension. *Psychology and Aging*, *27*(1), 106.

Jeffreys, H. (1961). *Theory of probability, Clarendon.* Oxford: Oxford University Press, Clarendon Press.

Kassambara, A. (2019). *Ggpubr: 'Ggplot2' based publication ready plots.* https://CRAN.R-project.org/package=ggpubr

Koch, I., Poljac, E., Müller, H., & Kiesel, A. (2018). Cognitive structure, flexibility, and plasticity in human multitasking—An integrative review of dual-task and task-switching research. *Psychological Bulletin*, *144*(6), 557.

Konishi, M., McLaren, D. G., Engen, H., & Smallwood, J. (2015). Shaped by the past: The default mode network supports cognition that is independent of immediate perceptual input. *PloS One*, *10*(6), e0132209.

Kuznetsova, A., Brockhoff, P. B., & Christensen, R. H. B. (2017). lmerTest package: Tests in linear mixed effects models. *Journal of Statistical Software*, *82*(13), 1–26. https://doi.org/10.18637/jss.v082.i13

Maillet, D., & Schacter, D. L. (2016). From mind wandering to involuntary retrieval: Age-related differences in spontaneous cognitive processes. *Neuropsychologia*, *80*, 142–156. https://doi.org/10.1016/j.neuropsychologia.2015.11.017

Marty-Dugas, J. (2020). *Refining Flow: The Re-conceptualization And Measurement Of Flow As Deep Effortless Concentration.*

Marty-Dugas, J., & Smilek, D. (2019). Deep, effortless concentration: Re-examining the flow concept and exploring relations with inattention, absorption, and personality. *Psychological Research*, *83*(8), 1760–1777.

McKiernan, K. A., D'Angelo, B. R., Kaufman, J. N., & Binder, J. R. (2006). Interrupting the "stream of consciousness": An fMRI investigation. *Neuroimage*, *29*(4), 1185–1191.

McVay, J. C., & Kane, M. J. (2009). Conducting the train of thought: Working memory capacity, goal neglect, and mind wandering in an executive-control task. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *35*(1), 196.

McVay, J. C., & Kane, M. J. (2012). Drifting from slow to "d'oh!": Working memory capacity and mind wandering predict extreme reaction times and executive control errors. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *38*(3), 525.

Mills, C., D'Mello, S. K., & Kopp, K. (2015). The influence of consequence value and text difficulty on affect, attention, and learning while reading instructional texts. *Learning and Instruction*, *40*, 9–20.

Mills, C., Raffaelli, Q., Irving, Z. C., Stan, D., & Christoff, K. (2018). Is an off-task mind a freely-moving mind? Examining the relationship between different dimensions of thought. *Consciousness and Cognition*, *58*, 20–33.

Morey, R. D., & Rouder, J. N. (2018). *BayesFactor: Computation of Bayes Factors for Common Designs.* https://CRAN.R-project.org/package=BayesFactor

Mrazek, M. D., Smallwood, J., Franklin, M. S., Chin, J. M., Baird, B., & Schooler, J. W. (2012). The role of mind-wandering in measurements of general aptitude. *Journal of Experimental Psychology: General*, *141*(4), 788–798. https://doi.org/10.1037/a0027968

Murray, S., Krasich, K., Schooler, J. W., & Seli, P. (2020). What's in a Task? Complications in the Study of the Task-Unrelated-Thought Variety of Mind Wandering. *Perspectives on Psychological Science*, 1745691619897966.

Nakamura, J., & Csikszentmihalyi, M. (2014). The Concept of Flow. In M. Csikszentmihalyi (Ed.), *Flow and the Foundations of Positive Psychology: The Collected Works of Mihaly Csikszentmihalyi* (pp. 239–263). Springer Netherlands. https://doi.org/10.1007/978-94-017-9088-8_16

O'Neill, K., Smith, A. P., Smilek, D., & Seli, P. (under review). *Dissociating the freely-moving thought dimension of mind-wandering from the intentionality and task-unrelated thought dimensions* [Paper submitted for publication].

Phillips, N. E., Mills, C., D'Mello, S., & Risko, E. F. (2016). On the influence of re-reading on mind wandering. *Quarterly Journal of Experimental Psychology*, *69*(12), 2338–2357.

Randall, J. G., Oswald, F. L., & Beier, M. E. (2014). Mind-wandering, cognition, and performance: A theory-driven meta-analysis of attention regulation. *Psychological Bulletin*, *140*(6), 1411.

R Core Team. (2019). *R: A language and environment for statistical computing*. R Foundation for Statistical Computing. https://www.R-project.org/

Rouder, J. N., Speckman, P. L., Sun, D., Morey, R. D., & Iverson, G. (2009). Bayesian t tests for accepting and rejecting the null hypothesis. *Psychonomic Bulletin & Review*, *16*(2), 225–237.

Schooler, J. W. (2004). Zoning Out while Reading: Evidence for Dissociations between Experience and Metaconsciousness Jonathan W. Schooler, Erik D. Reichle, and David V. Halpern. *Thinking and Seeing: Visual Metacognition in Adults and Children*, *203*.

Seli, P., Konishi, M., Risko, E. F., & Smilek, D. (2018). The role of task difficulty in theoretical accounts of mind wandering. *Consciousness and Cognition*, *65*, 255–262. https://doi.org/10.1016/j.concog.2018.08.005

Seli, P., O'Neill, K., Carriere, J. S., Smilek, D., Beaty, R. E., & Schacter, D. L. (2020). Mind-wandering across the age gap: Age-related differences in mind-wandering are partially attributable to age-related differences in motivation. *The Journals of Gerontology: Series B*.

Singmann, H., Bolker, B., Westfall, J., Aust, F., & Ben-Shachar, M. S. (2019). *Afex: Analysis of factorial experiments*. https://CRAN.R-project.org/package=afex

Smallwood, J., Brown, K. S., Tipper, C., Giesbrecht, B., Franklin, M. S., Mrazek, M. D., Carlson, J. M., & Schooler, J. W. (2011). Pupillometric evidence for the decoupling of attention from perceptual input during offline thought. *PloS One*, *6*(3), e18298.

Smallwood, J., McSpadden, M., & Schooler, J. W. (2007). The lights are on but no one's home: Meta-awareness and the decoupling of attention when the mind wanders. *Psychonomic Bulletin & Review*, *14*(3), 527–533.

Smallwood, J., & Schooler, J. W. (2006). The restless mind. *Psychological Bulletin*, *132*(6), 946.

Smith, A. C., Brosowsky, N. P., Ralph, B. C. W., Smilek, D., & Seli, P. (under review). *Re-examining the effect of motivation on intentional and unintentional task-unrelated thought: Accounting for thought constraint produces novel results.*

Smith, A. P., Brosowsky, N. P., Daniel, R., Meier, M. E., & Seli, P. (under review). *Fixation, flexibility, and creativity: The dynamics of mind wandering.*

Teasdale, J. D., Dritschel, B. H., Taylor, M. J., Proctor, L., Lloyd, C. A., Nimmo-Smith, I., & Baddeley, A. D. (1995). Stimulus-independent thought depends on central executive resources. *Memory & Cognition*, *23*(5), 551–559. https://doi.org/10.3758/

BF03197257

Thomson, D. R., Besner, D., & Smilek, D. (2013). In pursuit of off-task thought: Mind wandering-performance trade-offs while reading aloud and color naming. *Frontiers in Psychology*, *4*, 360.

Ullén, F., Manzano, Ö. de, Almeida, R., Magnusson, P. K., Pedersen, N. L., Nakamura, J., Csíkszentmihályi, M., & Madison, G. (2012). Proneness for psychological flow in everyday life: Associations with personality and intelligence. *Personality and Individual Differences*, *52*(2), 167–172.

Wammes, J. D., Boucher, P. O., Seli, P., Cheyne, J. A., & Smilek, D. (2016). Mind wandering during lectures I: Changes in rates across an entire semester. *Scholarship of Teaching and Learning in Psychology*, *2*(1), 13.

Wickham, H. (2016). *Ggplot2: Elegant graphics for data analysis*. Springer-Verlag New York. https://ggplot2.tidyverse.org

Wickham, H., François, R., Henry, L., & Müller, K. (2019). *Dplyr: A grammar of data manipulation*. https://CRAN.R-project.org/package=dplyr

Wickham, H., & Henry, L. (2019). *Tidyr: Tidy messy data*. https://CRAN.R-project.org/package=tidyr

Wilke, C. O. (2019). *Cowplot: Streamlined Plot Theme and Plot Annotations for 'ggplot2'*. https://CRAN.R-project.org/package=cowplot

Yanko, M. R., & Spalek, T. M. (2014). Driving with the wandering mind: The effect that mind-wandering has on driving performance. *Human Factors*, *56*(2), 260–269.

Zhang, H., Qu, C., Miller, K. F., & Cortina, K. S. (2020). Missing the joke: Reduced rereading of garden-path jokes during mind-wandering. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *46*(4), 638.