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BRIEF REPORT

Controlling the stream of thought: Working memory capacity predicts adjustment of mind-wandering to situational demands

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Abstract Although engaging in task-unrelated thoughts can be enjoyable and functional under certain circumstances, allowing one's mind to wander off-task will come at a cost to performance in many situations. Given that task-unrelated thoughts need to be blocked out when the current task requires full attention, it has been argued that cognitive control is necessary to prevent mind-wandering from becoming maladaptive. Extending this idea, we exposed participants to tasks of different demands and assessed mind-wandering via thought probes. Employing a latent-change model, we found mind-wandering to be adjusted to current task demands. As hypothesized, the degree of adjustment was predicted by working memory capacity, indicating that participants with higher working memory capacity were more flexible in their coordination of on- and off-task thoughts. Notably, the better the adjustment, the smaller performance decrements due to increased task demands were. On the basis of these findings, we argue that cognitive control does not simply allow blocking out task-unrelated thoughts but, rather, allows one to flexibly adjust mind-wandering to situational demands.

Keywords Mind-wandering · Executive control · Working memory · Adaptive cognition

Although many everyday tasks require people to focus and sustain their attention on the current task, thoughts sometimes unintentionally trail off (Schooler et al., 2011). This ubiquitous phenomenon has been studied under the terms *mind-wandering* or *task-unrelated thoughts* (TUTs). In some situations, people engage in TUTs about unfulfilled tasks or personal problems, and such TUTs may help people to achieve personal goals (cf. Klinger, 1999; Mooneyham & Schooler, 2013). For example, thinking about the grocery shopping list while transcribing text may save time later in the grocery store. In other situations, however, TUTs are associated with performance decrements to current tasks (Feng, D'Mello, & Graesser, 2013; McVay & Kane, 2012; Mrazek et al., 2012). Analogously, contemplating a shopping list while reading an article may be detrimental to comprehension. Given that mind-wandering can be useful for future tasks but also harmful to current tasks (cf. Mooneyham & Schooler, 2013), it seems advisable to adjust the engagement in TUTs to the demands of the task at hand. If current task demands are low, it may be beneficial to engage in TUTs about future tasks, but if current task demands are high, postponing TUTs may be more adaptive. In the present study, we therefore extended the investigation of mind-wandering to the adaptive adjustment of TUTs to varying situational demands.

Recent research identified working memory capacity (WMC) as a potent predictor for the engagement in TUTs (cf. Kane et al., 2007). WMC has been shown to predict various intellectual capabilities and is generally seen as an indicator of cognitive-processing capacity (e.g., Kane & Engle, 2003). While most researchers agree that TUTs occur rather spontaneously and are probably triggered by (personally relevant) environmental cues (Klinger, 1999), there is a debate about the relationship between WMC and TUT engagement. On the one hand, maintenance of TUTs may compete with current tasks for limited cognitive resources, and thus high-WMC individuals should be better able than low-WMC individuals to *sustain* TUTs without sacrificing task performance (Smallwood, 2010). On the other hand, TUTs may occur and persist automatically, but *inhibiting* TUTs in order to prevent interference of TUTs with ongoing task

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performance may require cognitive resources (McVay & Kane, 2010). Studies showing that high-WMC individuals are less prone to TUTs than low-WMC individuals (McVay & Kane 2009, 2012; Mrazek et al., 2012; but see Levinson, Smallwood, & Davidson, 2012, for the opposite finding) are in line with the latter view. These findings are usually explained in light of the assumption that WMC (partially) reflects cognitive control abilities (Kane & Engle, 2003), and thus high-WMC individuals should generally be better able to suppress TUTs. Taking this idea one step further, we argue that cognitive control may be required not only to generally inhibit TUTs while performing another task, but also to adjust the engagement in TUTs to task demands. That is, individuals with better cognitive control abilities should suppress TUTs especially when current task demands are high, and interference from TUTs is thus very likely to hamper task performance. If the current task requires only a few cognitive resources, however, task performance probably does not suffer from interference from TUTs, and thus there would be no need to suppress them. Going beyond the inhibitory control view, this *cognitive flexibility* view predicts that the relationship between WMC and TUT engagement depends heavily on current task demands and might even flip, depending on whether task demands are low or high.

Preliminary evidence that cognitive control abilities predict the *adjustment* of mind-wandering to task demands comes from a field study by Kane et al. (2007). In this study, mind-wandering was assessed using a portable device, and participants rated how challenging the current activity was. Results indicate that high-WMC individuals showed fewer TUTs than did low-WMC individuals only when ongoing activities were perceived as challenging. Nonetheless, task demand self-reports are probably not independent of WMC, and it thus remains an open question whether factual task demands moderate the relationship between cognitive control abilities and mind-wandering. Furthermore, it remains to be tested whether TUT reductions with increased task demands are, in fact, beneficial for task performance.

To test these hypotheses, we experimentally manipulated task demands (low vs. high) within participants and assessed TUTs, as well as task performance, under both conditions. Furthermore, we measured WMC (via an operation-span task; Unsworth, Heitz, Schrock, & Engle, 2005) and assessed task demand awareness by asking participants to estimate their performance in both tasks. This paradigm allows modeling the relationship of adjustment of TUTs to task demands and actual task performance in a joint latent-change model (McArdle, 2009). Within this model, we can now explicitly test a variety of predictions of the cognitive flexibility view. First, TUT adjustment should be predictive of performance decrements due to increased task difficulty. That is, the better participants adjust their TUTs, the smaller should be the decrement to ongoing task performance. Such a relationship would imply that TUT adjustment is indeed functional in terms of allowing maintenance of high levels of task performance even under increased demands. Second, according to the cognitive flexibility view, WMC should be predictive of TUT adjustment and performance decrements. That is, high-WMC participants should be better able to adjust their TUTs in line with situational demands, and they should show fewer performance decrements than low-WMC individuals when task demands increase.

Method

Participants

One hundred and ten participants were recruited at a German University, as well as off campus, and were tested in groups. Data of 2 participants were discarded because of floor performance (zero hits) in the 3-back task, resulting in $N = 108$ ($M_{\text{age}} = 23.\ 28$, $SD_{\text{age}} = 7.04$; 73 % female).

Materials

The automated operation-span (aOspan) task (Unsworth et al., 2005) was used to assess WMC. In this task, participants memorize letters while performing mathematical operations with an individualized response deadline (M + 2.5 SDs). Participants are presented with a math operation [e.g., (7*4) – 8] followed by a number (e.g., 20) and have to verify whether the number is the solution to the preceding operation. Two hundred milliseconds after either operation verification or the response deadline, the letter is randomly selected from a set of 12 and is presented for 250 ms. After a series of three to seven operation–letter pairs, all 12 letters are presented, and participants have to identify the previously presented letters in correct order. The sum of letters recalled in correct serial position was used as the WMC measure (Conway et al., 2005).

To assess mind-wandering, we used the thought probes from McVay and Kane (2009) asking participants to select an answer to the question *What were you just thinking about*? from seven response options: (a) *the current task*, (b) *my performance in the current task*, (c) *everyday stuff*, (d) *my current state of being*, (e) *my personal worries*, (f) *daydreams*, or (g) *other task-unrelated stuff*. Selections of the thought-probe response options (c)–(g) were counted as TUTs.[1]

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[1] One participant used the response category (b) during the first *n*-back block to indicate that he was thinking about his performance in the later *n*-back block. Therefore, (b) responses in the first *n*-back block were coded as TUTs. Excluding this participant does not alter the present results.

To manipulate task demands, we used a 1-back and a 3-back version of the *n*-back task in which letters were successively presented for 500 ms each, followed by a 3-s response window. In the 1-back version, participants had to press a green-labeled key (*J* key) if the presented letter matched the previous one. Otherwise, participants should press a red-labeled key (*N* key). In the 3-back version, participants had to press the green key if the presented letter matched the letter presented three trials earlier. Three-back trials did not occur during the 1-back task, and 1-back trials did not occur during the 3-back task; 2-back trials did not occur during either *n*-back task.

Procedure

After signing a consent form, participants performed the computerized aOspan task. Then participants filled in a personality questionnaire[2] (paper–pencil) before they received instructions for the *n*-back tasks in general and for a practice phase of the task during which they should press the green key for the letter “X” and the red key for all other letters. Next, the thought probes were introduced, and instructions further elaborated each response option (cf. McVay & Kane, 2009). Participants then performed 15 practice trials (5 were “X”-trials) of the *n*-back task, during which thought probes were presented after trials 5 and 13. Then, participants performed two *n*-back blocks (1-back, 3-back). Block order was randomly determined for each participant. Each block consisted of 12 buffer trials (not analyzed) and 120 experimental trials. One third of all trials were match trials, two thirds were nonmatch trials. For the nonmatch trials, letters were selected randomly from a set of 20. To avoid extensive series of trials of one type, each sequence of 12 trials consisted of 4 match and 8 nonmatch trials. Mind-wandering probes were presented after trials 24, 36, 48, 60, 72, 84, 96, 108, 120, and 132. Probes were always succeeded by 3 nonmatch trials to avoid interference of probes with *n*-back matches. Before each block, participants received detailed instructions for the following *n*-back task. Between blocks, participants took a break of 3 min and filled in a paper–pencil version of the Cognitive-Failure Questionnaire (CFQ; Broadbent, 1980).[3] Finally, participants estimated their *n*-back task accuracies for both blocks separately (on scales from 0 to 100) and filled in a demographic questionnaire, before they were debriefed and dismissed.

Analysis and results

We employed a latent-change model (McArdle, 2009) to simultaneously model interindividual differences in the effects of task difficulty on TUTs and on task performance.

In general, latent-change models represent the change between two (or more) assessments in terms of a latent-change score. In this framework, one assessment (e.g., TUTs/performance in the 3-back task) is considered a compound of the other assessment (e.g., TUTs/performance in the 1-back task) and a change score.[4] The change score is estimated from the observed variables (Y_i) in terms of a latent difference variable (η_Δ) by fixing the regression coefficient between both observed variables ($Y_{3\text{-back}}$, $Y_{1\text{-back}}$) and the regression coefficient of the latent difference variable to 1 (cf. Eq. 1):

$$Y_{3-back} = 1 \times Y_{1-back} + 1 \times \eta_\Delta \quad (1)$$

Including the mean structure in the model renders the intercept of the latent-change variable (μ_Δ) the mean change between the two observed variables, while the variance of the latent-change variable ($\sigma_\Delta{}^2$) represents the variance in change across individuals. The change variable thus represents a latent variable avoiding the problems associated with manifest difference scores (Cronbach & Furby, 1970), and further variables can be included in the model to account for variance in latent change.

The rate of TUTs was computed as the relative frequency of off-task thoughts in the 1-back and in the 3-back tasks. Performance in both tasks was computed in terms of *d′* scores.[5] Table 1 displays the means, standard deviations, and correlations between the manifest variables in the model.

Model specification and parameter estimation were conducted using *M*plus (Muthén & Muthén, 1998–2013). Figure 1 displays the latent-change model including WMC as a predictor and standardized parameter estimates.[6] The estimated intercept (μ_Δ) of the latent-change variable for TUTs was −.200, $z = 7.944$, $p < .001$, indicating that the

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[2] The personality questionnaire served as a break between WMC and TUT assessments and is not further considered here.

[3] Because the CFQ was correlated neither with WMC, $r(108) = .01$, $p = .919$, nor with task performance, $|rs| < .16$, $ps > .100$, it was not considered as a predictor in the following analyses.

[4] Because *n*-back task order was randomly determined for each participant, changing the order of variables in the analysis only reverses the direction of effects. Task order did not affect (or interact with) TUT rates, Fs < 1, or *n*-back performance, Fs < 1, and was thus not considered in the model. Others have reported order effects in within-designs, but with more extensive numbers of trials (McVay & Kane, 2009).

[5] To avoid perfect hit and false alarm rates, we added a constant of .5 to individual hit and false alarm frequencies and increased the denominator by 1 (Snodgrass & Corwin, 1988).

[6] The standardized regression weight of “*d′* 3-back” on “Change Perf” of 1.09 is a result of the partitioning of the variance of “*d′* 3-back” and does not represent a Heywood case, because none of the variance estimates is negative, and, unlike correlations, standardized regression weights can well be larger than 1 (although very rarely).

Table 1 Means (*M*), standard deviations (diagonal), and correlations of the measures included in the latent-change model

	M	1	2	3	4	5
1 *WMC*	**58.94**	**11.60**				
2 *TUTs 1-back*	**.50**	.179†	**.25**			
3 *TUTs 3-back*	**.30**	−.188†	.492***	**.27**		
4 *d' 1-back*	**2.44**	.186†	−.006	−.194*	**.51**	
5 *d' 3-back*	**2.01**	.402***	−.015	−.320**	.435***	**.57**

Note. Working memory capacity (WMC) = sum of letters recalled in correct serial position in the aOspan task (Unsworth, Heitz, Schrock, & Engle, 2005); TUTs = proportions of off-task thought responses to mind-wandering probes presented during the *n*-back tasks; *d'* = performance in the *n*-back tasks

$^{\dagger}p < .07$

$^{*}p < .05$

$^{**}p < .01$

$^{***}p < .001$

average rate of TUTs was .20 units lower in the 3-back task than in the 1-back task. This result suggests that mind-wandering was generally lower under high-demanding than under low-demanding task conditions. Additionally, the significant variance associated with the TUT change, $z = 7.432$, $p < .001$, indicates that participants differed substantially in their adjustment of TUTs to task demands.

As was expected, task performance was significantly higher in the 1-back than in the 3-back task, as is evident from the significant intercept of the latent-change variable (μ_{Δ} = 0.432), $z = 7.538$, $p < .001$, and participants differed significantly in their performance decrements, as is evident from the significant variance of the latent-change variable of task performance, $z = 7.091$, $p < .001$. Importantly, change in TUTs was negatively correlated with change in performance, $z = 2.967$, $p = .003$, with greater TUT adjustment being associated with fewer performance decrements. That is, stronger TUT adjustments were predictive of higher resistance to task-demand-associated performance decrements.

In line with our hypothesis, WMC was a significant predictor of TUT change, $z = 3.536$, $p < .001$, indicating that higher WMC participants showed higher levels of TUT adjustment than did lower WMC participants. Thus, the degree to which participants adaptively adjusted their mind-wandering can be (in part) explained by WMC. Furthermore, WMC significantly predicted change in performance, $z = 3.301$, $p = .001$, with higher WMC individuals exhibiting fewer performance decrements under increased task demands than lower WMC individuals. Accounting for the effect of WMC on TUT adjustment and the effect of WMC on performance change rendered the correlation between TUT adjustment and performance change only marginally significant, $z = 1.626$, $p = .104$. However, restricting the regression weight from performance change to WMC to zero rendered the indirect effect of WMC on performance change via TUT adjustment significant, $p = .029$. In combination, these results suggest that a substantial part of the shared variance in performance change and TUT adjustment can be traced back to variance in WMC.

Moreover, the simple correlations between WMC and TUT engagement (cf. Table 1) replicate contradicting results from previous research (Levinson et al., 2012; McVay & Kane, 2009) within one experiment. As was hypothesized, WMC and TUT engagement were positively related when task demands were low but negatively related when task demands were high.

Finally, we compared performance self-estimates between the 1-back ($M = .73$, $SD = .20$) and the 3-back ($M = .47$, $SD = .26$) tasks and found that estimates reflected factual task difficulty differences, $t(109) = 9.22$, $p < .001$, $d_z = 0.88$. Task performance and performance estimates were highly

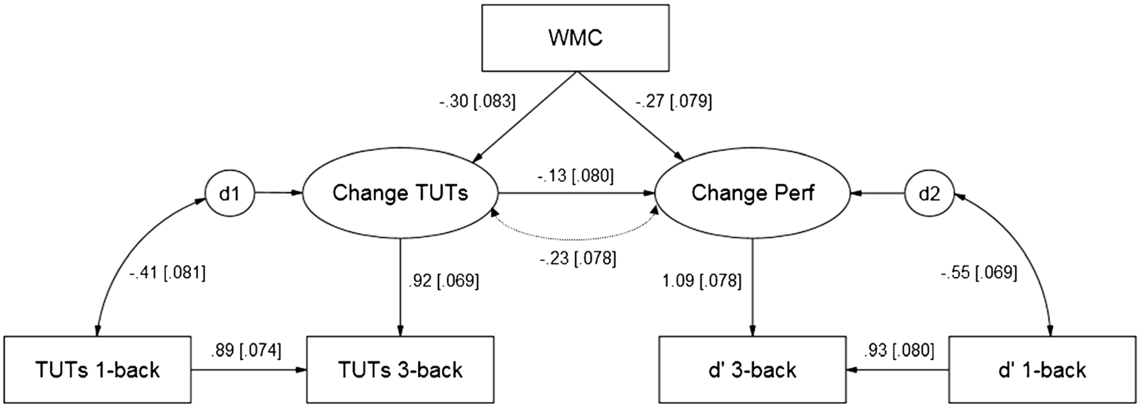

Fig. 1 Latent-change model including *working memory capacity* (WMC) as predictor for variability in change in task-unrelated thoughts (TUTs) and in task performance (Perf); latent variables are displayed as ellipses, and observed variables are displayed as rectangles. The dotted arrow represents the path coefficient between "Change TUTs" and "Change Perf" when WMC is not controlled for. Note that both change variables are negative. The negative path coefficient from "WMC" to "Change TUTs" thus indicates that higher WMC scores are predictive of more negative "Change TUTs" scores. The more negative the "Change TUTs" score, the more adjustment (reduction) in TUTs. Similarly, higher WMC scores are predictive of less "Change Perf" and, thus, fewer task decrements in the 3-back task. Standard errors are displayed in brackets

correlated for both tasks [1-back, $r(108) = .49$, $p < .001$; 3-back, $r(108) = .47$, $p < .001$], indicating that performance estimates were calibrated quite well.

Discussion

Mind-wandering represents one important aspect of human behavior regulation, and in line with the hypothesis that the flexible adjustment of TUTs should be beneficial to task performance, we found stronger TUT adjustment to be associated with fewer performance decrements under increased task demands.

As predicted by interindividual difference views of mind-wandering (e.g., Kane & McVay, 2012), we also found strong individual tendencies to engage in TUTs across tasks of different demands, as evident from the high correlation between TUTs in the 1-back and the 3-back tasks (cf. Table 1). Performance self-estimates, however, suggest that participants were aware of the higher demands in the 3-back, as compared with the 1-back, task. Accordingly, mean TUT rates were higher during the low-demanding than during the high-demanding task. Interestingly, TUT adjustments to situational demands varied substantially across participants. More important, we found evidence for the hypothesis that cognitive control abilities are specifically involved in the *flexible adjustment* of mind-wandering to task demands. As was hypothesized, high-WMC participants showed higher levels of TUT adjustment than did low-WMC participants. Thus, a more flexible coordination of the stream of thought appears to be characteristic of high-WMC individuals: They engage in TUTs when situational demands are low but reduce TUTs in attention-demanding situations. This is novel empirical evidence that individuals adjust their engagement in TUTs to task demands over and above their general propensity to engage in TUTs.

Notably, higher WMC was associated with better task performance in both the 1-back and the 3-back tasks (cf. Table 1), a result expected on the basis of previous findings that TUT engagement is usually negatively associated with task performance under demanding task conditions (e.g., McVay & Kane, 2009). Going beyond previous research, the present results show that variations in WMC explained substantial parts of TUT changes *and* performance changes. In fact, the correlation between TUT changes and performance changes was no longer significant when WMC was controlled for. Additionally, there was an indirect effect from WMC via TUT change to performance change when the regression weight from WMC to performance change was restricted to zero. In sum, these findings imply that the reduced susceptibility to increased task demands of high-WMC individuals, relative to low-WMC individuals, might be in part due to their higher TUT adjustment abilities. Given the correlational nature of these data, however, we cannot be sure whether better adjustment of TUTs leads to performance improvements or vice versa, but the present interpretation is certainly more in line with previous interpretations of the TUT–task-performance relationship (cf. Feng et al., 2013).

The present findings may further help understanding why some researchers find a negative WMC–TUT relation (e.g., McVay & Kane, 2009; Mrazek et al., 2012), whereas others find the opposite relation (Levinson et al., 2012). Indeed, negative WMC–TUT associations were especially strong in previous studies where mind-wandering was assessed during ongoing tasks that imposed high WM demands, such as go/no-go tasks (McVay & Kane 2009, 2012), while WMC and TUTs during a less demanding vigilance tasks were uncorrelated (McVay & Kane, 2012). Levinson et al., who employed a low-demanding visual search task, even found a positive WMC–TUT association. Thus, WMC–TUT associations appear to vary with the demands of the current task. In line with this assumption, we observed a *positive* correlation between WMC and TUTs in the rather undemanding 1-back task but a *negative* correlation in the more demanding 3-back task (see Table 1). The present findings are thus not fully compatible either with the idea that the maintenance of TUTs requires executive resources (Smallwood, 2010; Smallwood & Schooler, 2006) or with the idea that the inhibition of TUTs requires executive resources (McVay & Kane, 2010). The positive WMC–TUT relation under low-demanding task conditions is in line with the assumption that performance of the current task and maintenance of TUTs draws on the same limited cognitive resources (Smallwood, 2010). The negative WMC–TUT relation under high-demanding task conditions, on the other hand, is more in line with the assumption that the inhibition of TUTs requires cognitive resources (McVay & Kane, 2010). Key to the understanding of the apparently complex relationship between mind-wandering and WMC seems to be the consideration of regulative processes in the use of cognitive resources and, thus, in the adjustment of TUTs to task demands. Given that individuals differ in their executive resources for controlling TUTs, it is at the discretion of high-WMC individuals to exert cognitive control over TUTs depending on situational demands, whereas low-WMC individuals do not have the necessary resources to exert control over their TUTs. Given that mind-wandering can be beneficial for mastering our daily lives (Mooneyham & Schooler, 2013), adjusting TUTs to the demands of current tasks can be an efficient strategy for optimizing the use of cognitive resources. In this view, individuals with better cognitive control abilities not only might be better able to suppress TUTs, but also might be better aware of when TUTs will not interfere with the task at hand (i.e., during relatively easy tasks). In these situations, it may be beneficial to engage in additional TUTs, because they do not come at a cost to performance of the current task.

In a related vein, the variation in the WMC–TUT relationship might also help to understand why the predictive power of WMC for performance in other cognitive tasks varies with the demands of these tasks (e.g., Bunting, 2006). Although high-WMC individuals may have a stronger ability to focus on the task at hand than low-WMC individuals, they may nonetheless choose not to do so, given that the task does not require their complete cognitive resources. Future research, however, is, of course, necessary to test this assumption.

A general caveat in the interpretation of WMC–TUT associations is that effects could be driven by general TUT-related performance decrements across the tasks (Mrazek et al., 2012). Put plainly, some participants might have constantly mind-wandered during the aOspan and during the two *n*-back tasks at the cost of their performance in all tasks, creating a spurious correlation. However, WMC was *positively* correlated with task performance under both demanding and nondemanding task conditions. At the same time, WMC was *positively* correlated with TUTs under low-demanding and *negatively* correlated with TUTs under high-demanding task conditions. This pattern of results renders it unlikely that WMC–TUT associations were mere reflections of general TUT-related task performance decrements.

Taken together, our results suggest that TUTs are flexibly adjusted to task demands and that high-WMC individuals are better able to control their stream of thoughts than are lower-WMC individuals, which helps them to avoid performance decrements in cognitively demanding situations. These findings are in line with the view that human cognition in general and mind-wandering in particular are adaptive (Anderson, 1991; Kane & McVay, 2012; Mooneyham & Schooler, 2013). On a more general level, these data suggest that the relationship between person-related factors and the tendency to mind-wander should consider person-by-situation interactions. This idea is in line with established personality theories arguing that not only stable cross-situational behavior, but also stable patterns of situation–behavior relations are reflections of individual consistency (Mischel, Shoda, & Mendoza-Denton, 2002).

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