Mind wandering impedes explicit but not implicit sequence learning

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Abstract

A common observation is that mind wandering increases with time on task. This phenomenon is typically explained as an executive resource trade-off: as people practice a task, it becomes automated, freeing up additional resources for mind wandering. However, there is a lack of evidence that learning rates correspond with increases in mind wandering. In the current study, we examined the association between mind wandering, task-automatization, and awareness using a serial reaction time task. Overall, we found that performance increased while at the same time depth of mind wandering increased, providing novel evidence for the task-automatization account. We also found that depth of mind wandering was negatively associated with learning in the explicit group, but not the implicit group. This result suggests that mind wandering impedes explicit but not implicit learning. Finally, we found novel evidence that performance evaluations can influence self-reports of mind wandering. Data, analysis code, manuscript preparation code, and pre-print available at osf.io/xxxx

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Mind wandering, although multi-faceted, typically refers to an unintended shift in attention from external stimuli towards task-unrelated thoughts (Seli et al., 2018; Smallwood, Baracaia, Lowe, & Obonsawin, 2003; Smallwood & Schooler, 2006). Though mind wandering can often disrupt focal task performance (Mooneyham & Schooler, 2013), it can be beneficial in some cases. For example, mind wandering can help with future planning and problem-solving (Smallwood & Schooler, 2015) or provide relief from attentional habituation (Mooneyham & Schooler, 2016). Explanations of when and why people mind wander vary (e.g., McVay & Kane, 2010; Seli et al., 2018). From a prominent point of view, how-

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ever, engaging in mind wandering consumes attentional resources that would otherwise be directed towards the focal task (Smallwood & Schooler, 2006). Thus, people perform worse on tasks when they are mind wandering because the allocation of resources to task-unrelated thoughts leaves fewer resources available for the focal task (Mooneyham & Schooler, 2013). People also tend mind wander more during an easy versus hard task, because an easy task requires fewer attentional resources, leaving more available for task-unrelated thoughts (Brosowsky et al., n.d.-b; Smallwood, Nind, & O'Connor, 2009).

Similarly, a common and theoretically relevant observation is that mind wandering progressively increases throughout the experimental task (Antrobus, 1968; Cunningham, Scerbo, & Freeman, 2000; Smallwood et al., 2004, 2003). This phenomenon is also explained in terms of an attentional resource trade-off: as participants gain experience and practice, some aspects of performing the task become automatic (i.e., performed quickly, effortlessly, and relatively autonomously) diminishing the need for attention (Logan, 1988; Logan & Compton, 1998; Moors & De Houwer, 2006; Newell & Rosenbloom, 1981; Schneider & Shiffrin, 1977; Shiffrin & Schneider, 1977) and freeing up resources for mind wandering (Smallwood & Schooler, 2006). From this point of view, the change in mind wandering over time corresponds to the rate of learning in the focal task.

As intuitive as the task automatization account is, however, there is an issue with this explanation. As the task becomes well-practiced and automatic, we expect that performance should *improve*. However, in mind wandering experiments, performance often becomes *worse* with increasing time on task (Krimsky, Forster, Llabre, & Jha, 2017; McVay & Kane, 2012; Metcalfe & Xu, 2016; Risko, Anderson, Sarwal, Engelhardt, & Kingstone, 2012; Teasdale et al., 1995; Thomson, Seli, Besner, & Smilek, 2014). For example, Cunningham et al. (2000) used a visual-discrimination task with low target probability (i.e., a vigilance task) and found that, although self-caught instances of task-unrelated thoughts increase across the task, reaction times slowed, and detection rates decreased (for a similar result, see McVay & Kane, 2012). Similarly, using a Sustained Attention to Response Task (SART), Smallwood et al. (2004) found that both task-unrelated thoughts and response errors increased from the first to second half of the experiment. Finally, using a metronome response task, Brosowsky et al. (n.d.-a) found that performance declined as the experiment progressed (as indexed by response variability) as depth of mind wandering increased.

Taken together, the available evidence does not support the argument that people engage in more mind wandering *because* additional resources become available through task automatization. Indeed, if there is a trade-off of attentional resources, the increase in mind wandering seems to come at a cost to focal-task performance. Alternatively, others have proposed that the ongoing evaluation of participants' own performance affects their responses to mind wandering thought probes. That is, participants might infer from their poor performance that they were mind wandering (e.g., Helton, 2018). From this view, the increase in mind wandering over time might be *caused* by the decrease in performance.

However, it is unclear whether the task-automatization account has been properly assessed. For example, the standard tasks used to research mind wandering (e.g., SART, vigilance tasks, metronome response tasks) are unlikely to be appropriate for evaluating the relationship between skill-acquisition and mind wandering. Unsurprisingly, these tasks are designed in such a way that participants have ample opportunity to mind wander; that is, they are simple, monotonous, and require very little practice or instruction to complete. They are not designed to measure skill-acquisition in the focal task and, given their simplicity, it is unlikely that variations in learning rates could be measured.

Therefore, the primary aim of the current study was to examine the relationship between task automatization and mind wandering. We used a sequence learning task allowing us to measure the effects of practice during explicit and implicit learning. Implicit learning refers to situations where one has acquired information without being aware of what was learned (Keele, Ivry, Mayr, Hazeltine, & Heuer, 2003; Nissen & Bullemer, 1987; Seger, 1994). Implicit learning has been demonstrated across a variety of domains (Cleeremans, Destrebecqz, & Boyer, 1998) but commonly investigated using a serial reaction time (SRT) task (Nissen & Bullemer, 1987; for a review, see Schwarb & Schumacher, 2012). In this task, a target can appear in one of four locations and participants identify the location of a target by pressing a corresponding key. Critically, targets occur in a fixed sequence that repeat throughout the experiment until eventually the sequence changes to a new, unpracticed sequence of target locations. Participants typically perform better on the practice sequence as compared to the unpracticed sequence. However, despite this performance advantage participants are often unable to reconstruct the sequence and report no awareness of the repeating sequence, ruling out explicit learning. The serial reaction time task is well-suited for our goals because the motor sequence can become automated through practice, regardless of whether the learner intends it or not. Furthermore, these well-established experimental designs are sensitive to small variations in learning rates via multiple measures: the improvement in performance over time and the disruption caused by changing to an unlearned sequence (i.e., "transfer" effects; Pasquali, Cleeremans, & Gaillard, 2019).

Only one study to date has examined mind wandering using a serial reaction time task. Franklin, Smallwood, Zedelius, Broadway, & Schooler (2016) used a serial reaction time task to determine whether mind wandering would be associated with rates of implicit sequence learning. They had participants complete a four-choice SRT task with a 12-element repeating sequence. Throughout the task the practiced sequence would alternate with a new random sequence (six practice sequences followed by two unpracticed sequences) and at the end of the experiment they measured awareness using an explicit memory test. Learning was assessed by comparing performance on the random sequences to the practice sequence and was found to be negatively associated with mind wandering; participants who reported higher mind wandering showed smaller learning effects.

Critically however, the authors did not report changes in performance or mind wandering as a function of time on task and, therefore, cannot speak to whether increases in automatization result in higher reports of mind wandering. More specifically, the interleaved random sequences began immediately (the first two sequences were random) and continued throughout the task. Consequently, their measure of sequence learning includes early–presumably prior to any learning–as well as later performance, presumably after participants have learned the sequence.

In addition, there are several reasons to suggest that the research by Franklin et al. does not close the book on whether mind wandering impedes implicit learning. For one, the original study did not have an explicit (intentional) learning group to compare its results to, and is therefore unable to draw direct comparisons between implicit and explicit learning. Furthermore, the authors themselves note that they cannot be sure that participants did not gain some explicit knowledge. The measurement of awareness in serial reaction time tasks is still a contentious issue (Pasquali et al., 2019; Schwarb & Schumacher, 2012). However, the author's employed an awareness questionnaire and a single sequence generation task which is atypical and better awareness assessments have been established (see Pasquali et al., 2019). Finally, the author's alternated the practice sequence and random sequences in a predictable fashion (two random, six practice, two random, etc.) and did not measure changes in performance or mind wandering over time. Therefore, our secondary aim was to conceptually replicate and reevaluate whether mind wandering impedes implicit learning.

Here, we had participants complete a serial reaction time task with five locations. Participants practiced a 10-element repeating sequence for 13 blocks of 80 trials, before switching to a new unpracticed sequence in the 14th block and ending with the practice sequence in the 15th block. To assess awareness, participants completed two sequence generation tasks: an inclusion task, where participants generate the practice sequence for 100 trials, and the exclusion generation task, where participants generate the pattern in reverse (Pasquali et al., 2019). Whereas participants in the "explicit" condition were given instructions about memorizing the repeating sequence, participants in the "implicit" condition were not given any information about the sequences. Our study design improves and extends the prior work in several important ways: first, we measured both mind wandering and task performance as a function of time on task to address our primary question of interest; second, we included both explicit and implicit learning groups, allowing us to draw direct comparisons; and third, we adopted more robust measures of awareness, allowing us to more confidently rule out explicit learning in the implicit condition.

Method

Participants

Participants were 200 individuals who completed a Human Intelligence Task (HIT) posted on the Amazon Mechanical Turk. Participants were paid $3.25 (U.S. dollars) for completing the HIT, which lasted approximately 25 minutes. Participants were told the experiment would take less than 30 minutes but were not informed about how many trials they would be presented or often they would be asked to report their thoughts.

Serial Reaction Time (SRT) Task

The primary task was a serial reaction time task with five response options. The display contained five rectangles, each corresponding to a response on the keyboard (left-to-right: C, V, B, N, and M), displayed in dark grey (#555) on an off-white background (#f4f4f4). Each rectangle was 125.6 x 196 pixels and displayed 14.4 pixels apart. Each rectangle was initially outlined in dark grey and filled with off-white. On each trial, one rectangle changed color (dark grey or green) and participants were instructed to press the corresponding key as quickly and as accurately as possible. Once the participant pressed the correct key, the next target would immediately appear.

The experiment followed a typical SRT paradigm: participants completed 13 blocks of a repeating sequence, followed by a transfer block containing a new sequence (block 14), followed by a return to the original sequence (block 15). The entire experiment consisted of 15 blocks of 80 trials (1200 trials). Blocks 1 through 13 and block 15 contained a repeating

10-element, referred to as the "practice sequence". The 14th block, consisted of a new sequence, the reverse of the original (i.e., the "reverse sequence").

We used 10-element refined reversible second-order conditional (RSOC) sequences as described by Pasquali et al. (2019; see also Jiménez, Méndez, Pasquali, Abrahamse, & Verwey, 2011). These are second-order conditional sequences, traditionally used in SRT tasks (), and as such, each element appears with the same frequency–twice per sequence loop–and each transition occurs with equal frequency. In addition, however, refined ROC sequences contain no common transitions with its own reverse (i.e., "reversable"), but is otherwise fully analogous to the original. Finally, refined ROC sequences do not contain any ascending or descending runs (i.e., "refined"). Ascending and descending runs are excluded to eliminate potential abstract cues and keystroke facilitations that may enable chunking strategies (abstractly homogeneous; "no transition would be responded faster than others in the absence of learning"; cf., Jiménez, 2008). Each participant was randomly assigned a refined RSOC sequence from the total set of 840.

Participants were either assigned to the implicit (incidental) or explicit (intentional) learning conditions. The task and instructions were almost identical for both groups with two exceptions: First, in the explicit learning condition, a green rectangle appeared in place of the black rectangle to indicate the beginning of the sequence (no green rectangle appeared in the transfer block, but participants were not told in advance about the change in task). Second, participants in the explicit condition also received the following additional instructions:

> Important: the same sequence of locations/responses will repeat throughout the experiment. You will know when you are at the beginning of the sequence because the color of the rectangle will be green instead of black.
>
> As you complete the task you should try to memorize the repeating sequence so that you can respond as quickly as possible.

Generation Tasks

After the SRT task, awareness was assessed with two unexpected sequence generation tasks. In the inclusion generation task, participants were instructed to generate the practice sequence over 100 trials. The display began with one of the five rectangles randomly filled and participants were instructed to press the button corresponding to the next location that would have appeared in the practice sequence and to continue with the sequence for 100 trials. Participants were given the following instructions:

> Now we are going to test your knowledge of the sequence you've been practicing.
>
> In this part of the experiment, we want you to generate the practiced sequence from memory for 100 trials.
>
> The session will begin at a random location. You will respond with the next location that would have come right after it in the sequence you have practiced. Then you will respond again with the location that would come next, and so on, generating the sequence you have practiced.
>
> If you are unsure of the next location, try to rely on your intuition and respond as best as you can.

> The display will be identical to the practice and the boxes will change color based on your response.

The instructions differed slightly for the implicit learning group. For them, we included an additional statement to assure participants that they were not required to learn the sequence to receive payment ("You may or may not have noticed that there was a sequence of locations/responses that repeated throughout the experiment (if you didn't notice, that's ok)").

Participants then completed the exclusion generation task. This was the same as the inclusion task, except here participants were instructed to generate the reverse sequence from the one they had practiced:

> In this part of the experiment, we want you to generate the reversed pattern of the previously learned sequence from memory for 100 trials.
>
> The session will begin at a random location. You will respond with the location that would have come before it in the sequence. After that, you will respond again with the one that would have come before that, and so on, generating the sequence in reverse.
>
> If you are unsure of the next location, try to rely on your intuition and respond as best as you can.
>
> The display will be identical to the practice and the boxes will change color based on your response.

Performance on the generation tasks were assessed by computing the number of practiced and reverse sequence triplets. The number of triplets we expected they would produce by chance alone was computed as the number of triplets in the sequence divided by the total number of possible triplets, that is, 10 / (5 $\times$ 4 $\times$ 3) = 16.667%.

Thought probes

Throughout the MRT, depth of mind wandering was sampled using intermittently presented thought probes. Thought probes were presented at the end of every block of 80 trials. When a thought probe was presented, the task temporarily stopped, and the participant was presented with the following question: "To what extent were you mind wandering?" Participants were instructed to report their depth of mind wandering by using a sliding scale, the anchors for which were "Not at all Mind Wandering" (which corresponded with a value of 0) and "Fully Mind Wandering" (which corresponded with a value of 100).

At the beginning of the experiment, participants were given the following instructions, followed by a working example of the thought probe response interface:

> While you are completing this task, you may find yourself thinking about things other than the task. These thoughts are referred to as "task-unrelated thoughts" or "mind wandering". Having task-unrelated thoughts is perfectly normal, especially when one must do the same thing for a long period of time.

> We would like to determine how frequently you were thinking about the task versus how frequently you are thinking about something unrelated to the task (mind wandering). To do this, every once in a while, the task will temporarily stop and you will be presented with a thought-sampling screen that will ask you to indicate to what extent you have been focused on the task (not at all mind wandering) or focused on task-unrelated thoughts (fully mind wandering).
>
> Being focused on the task means that you were focused on some aspect of the task at hand. For example, if you have been thinking about your performance on the task, or about when you should make a button press, these thoughts would count as being on-task.
>
> On the other hand, experiencing task-unrelated thoughts means that you were thinking about something completely unrelated to the task. For example, thinking about what to eat for dinner, about an upcoming event, or about something that happened to you earlier in the day. Any thoughts that you have that are not related to the task you are completing count as task unrelated.
>
> When the thought-sampling screen is presented, we will ask you to indicate the extent to which you have been mind wandering. You will indicate the extent you have been mind wandering on a scale from 0 to 100 (0 being not at all mind wandering, 100 being fully mind wandering).

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, Mächler, Bolker, & Walker, 2015; Fox & Weisberg, 2019; Kuznetsova, Brockhoff, & Christensen, 2017; Singmann, Bolker, Westfall, Aust, & Ben-Shachar, 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 osf.io/xxxx.

Results

Generation Tasks

In the inclusion generation task, the explicit, M = 44.01, 95% CI [37.40, 50.63], $t(92) = 8.21$, $p < .001$, and implicit groups, $M = 22.65$, 95% CI [18.79, 26.51], $t(98) = 3.08$, $p = .003$, both produced practice sequence triplets above chance. However, the explicit group produced significantly more triplets than the implicit group, $\Delta M = 21.36$, 95% CI [13.86, 28.86], $t(190) = 5.62$, $p < .001$. Additionally, both the explicit, $M = 7.29$, 95% CI [5.57, 9.00], $t(92) = -10.88$, $p < .001$, and implicit groups, $M = 11.39$, 95% CI [9.79, 12.98], $t(98) = -6.56$, $p < .001$ produced fewer triplets from the reverse sequence than would be expected by chance. The explicit group however, produced fewer triplets than the implicit group, $\Delta M = -4.10$, 95% CI [−6.42, −1.78], $t(190) = -3.48$, $p = .001$.

Turning to the exclusion generation task, participants in the explicit group produced more reverse sequence triplets than would be expected by chance, M = 24.55, 95% CI

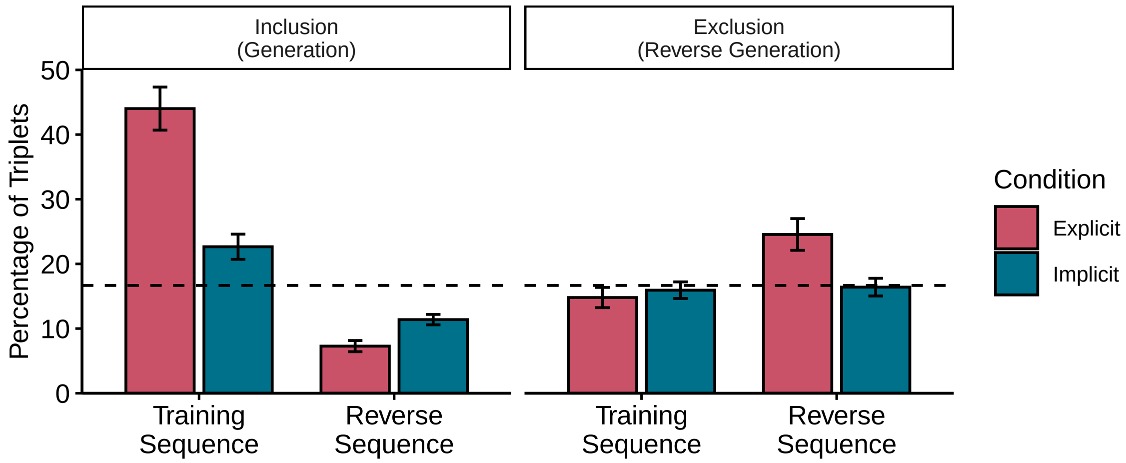

Figure 1. Results of the sequence generation tasks used to assess awareness across the explicit and implicit learning groups. Plots show the percentage triplets produced that match triplets from the training or reverse sequence when asked to produce the training sequence (inclusion generation task) or the reverse sequence (exclusion generation task).

[19.68, 29.42], $t(92) = 3.22$, $p = .002$; the implicit group, however, did not, $M = 16.41$, 95% CI [13.69, 19.12], $t(98) = -0.19$, $p = .850$. Furthermore, the explicit group produced more reverse triplets than the implicit group, $\Delta M = 8.15$, 95% CI [2.69, 13.60], $t(190) = 2.95$, $p = .004$. The number of practice sequence triplets however, did not differ from chance for either the explicit, $M = 14.80$, 95% CI [11.69, 17.91], $t(92) = -1.19$, $p = .236$ or implicit groups, $M = 15.93$, 95% CI [13.39, 18.48], $t(98) = -0.57$, $p = .569$. Similarly, there was no significant difference between conditions, $\Delta M = -1.14$, 95% CI [−5.10, 2.83], $t(190) = -0.56$, $p = .573$.

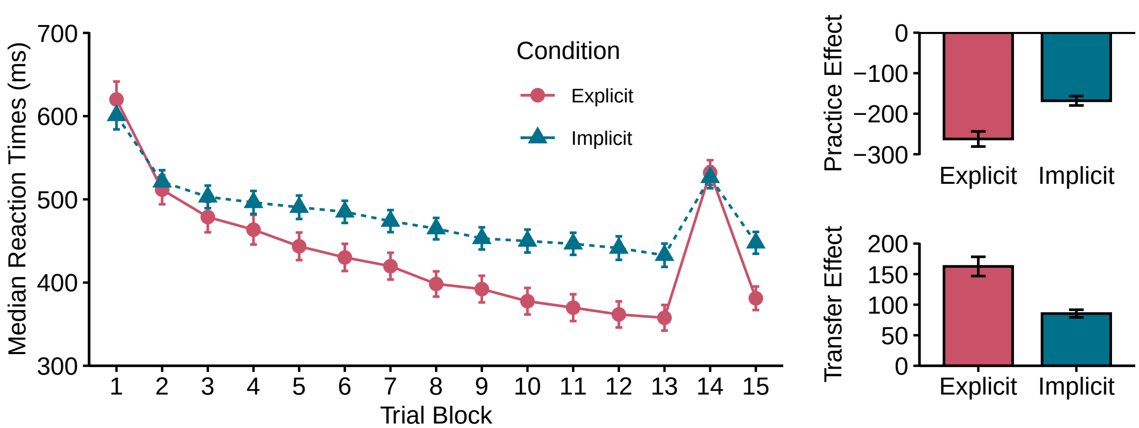

Figure 2. Results of the serial reaction time task. Median reaction times are plotted across trial blocks on the left. Practice effects (reaction times in the 1st block are subtracted from the 13th block) and transfer effects (reaction times in the 14th block are subtracted from the average of the 13th and 15th blocks) are plotted on the right.

Serial Reaction Time (SRT) Task

Prior to all analyses, we removed any participants with accuracy less than 80% (removing 7 participants) and one participant who did not complete all the trials. We additionally removed any responses with reaction times longer than 3000 ms, removing 0.27% of observations and removed the first trial following a thought probe. To determine how performance changed across the experiment, we analyzed a "practice effect" and a "transfer effect". The practice effect is the change in performance from the first to the 13th block and the transfer effect is the change in performance from blocks 13 and 15 (averaged) compared to the reversed block, block 14.

We found significant practice effects for both the explicit, $M_d = -262.32$, 95% CI $[-299.28, -225.36]$, $t(92) = -14.10$, $p < .001$, $d = -0.68$, 95% CI $[-0.9, -0.46]$, and the implicit, $M_d = -262.32$, 95% CI $[-299.28, -225.36]$, $t(92) = -14.10$, $p < .001$, $d = -0.68$, 95% CI $[-0.9, -0.46]$. Comparing conditions, we found the practice effect for explicit group was significantly larger than the implicit, $\Delta M = -94.31$, 95% CI $[-137.05, -51.58]$, $t(190) = -4.35$, $p < .001$, $d = -0.63$, 95% CI $[-0.92, -0.34]$. Turning to the transfer effect, median reaction times were significantly slower in the reversed block (block 14), for the explicit group, $M_d = 162.64$, 95% CI $[131.38, 193.90]$, $t(92) = 10.33$, $p < .001$, $d = 0.69$, 95% CI $[0.45, 0.94]$, as well as the implicit group, $M_d = 85.47$, 95% CI $[72.98, 97.96]$, $t(98) = 13.58$, $p < .001$, $d = 0.19$, 95% CI $[0.1, 0.29]$. Comparing effects across groups, the transfer effect was significantly larger for the explicit group, $\Delta M = 77.17$, 95% CI $[44.46, 109.87]$, $t(190) = 4.65$, $p < .001$, $d = 0.67$, 95% CI $[0.38, 0.96]$.

We also analyzed accuracy scores in a similar manner. We found significant practice effects, in that performance was better in 1st compared to the 13th block, for both the explicit $M_d = -0.05$, 95% CI $[-0.07, -0.03]$, $t(92) = -4.41$, $p < .001$, $d = -0.43$, 95% CI $[-0.68, -0.18]$, and implicit groups, $M_d = -0.04$, 95% CI $[-0.05, -0.02]$, $t(98) = -3.77$, $p < .001$, $d = -0.41$, 95% CI $[-0.67, -0.14]$, evidencing a speed-accuracy trade-off; However, this effect did not differ across groups, $\Delta M = 0.01$, 95% CI $[-0.02, 0.04]$, $t(190) = 0.87$, $p = .387$, $d = 0.13$, 95% CI $[-0.16, 0.41]$. More generally, performance was best in the first three blocks, but remained high (88-90% accurate) throughout the experiment (like Pasqueli et al. 2019). We also found significant transfer effects for both the explicit, $M_d = -0.06$, 95% CI $[-0.08, -0.04]$, $t(92) = -5.93$, $p < .001$, $d = -0.3$, 95% CI $[-0.47, -0.12]$ and implicit, $M_d = -0.07$, 95% CI $[-0.09, -0.05]$, $t(98) = -7.35$, $p < .001$, $d = -0.48$, 95% CI $[-0.7, -0.27]$ groups showing better accuracy in blocks 13 and 15, compared to block 14, the reverse block; and no significant difference in transfer effects between groups, $\Delta M = 0.01$, 95% CI $[-0.02, 0.04]$, $t(190) = 0.63$, $p = .531$, $d = 0.09$, 95% CI $[-0.19, 0.38]$.

Thought Probes

We adopted the same analysis plan as above to determine how depth of mind wandering changed throughout the experiment (see Figure 3). We first analyzed the practice effects and found a significant increase in the reported depth of mind wandering for both explicit $M_d = 22.91$, 95% CI $[15.60, 30.23]$, $t(92) = 6.22$, $p < .001$, $d = 0.68$, 95% CI $[0.4, 0.97]$, and implicit groups, $M_d = 19.24$, 95% CI $[12.36, 26.12]$, $t(98) = 5.55$, $p < .001$, $d = 0.51$, 95% CI $[0.26, 0.76]$; but no significant difference between groups, $\Delta M = -3.67$, 95% CI [-13.64,

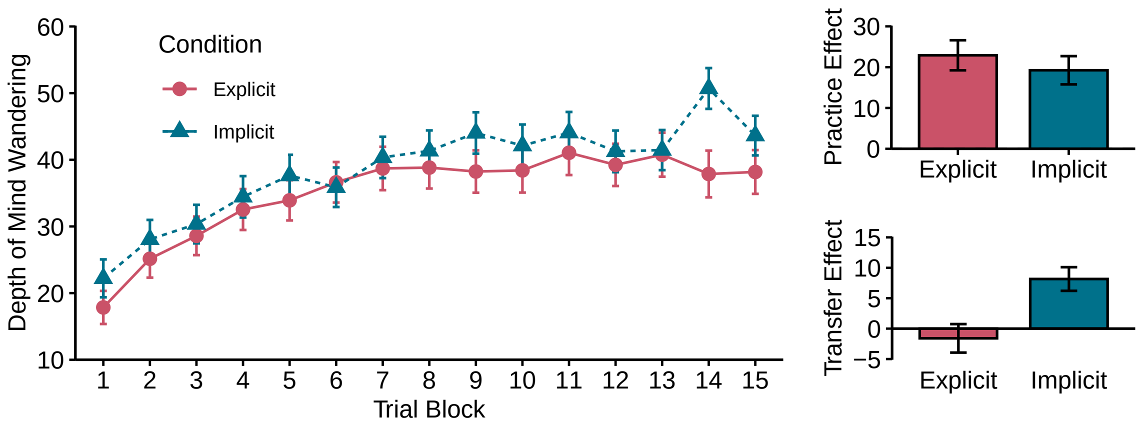

Figure 3. Results from the depth of mind wandering thought probes. Thought probe responses are plotted across trial blocks on the left. Practice effects (reported depth of mind wandering in the 1st block is subtracted from the 13th block) and transfer effects (reported depth of mind wandering in the 14th block is subtracted from the average of the 13th and 15th blocks) are plotted on the right.

6.30], $t(190) = -0.73$, $p = .468$, $d = -0.1$, 95% CI [−0.39, 0.18]. Turning to the transfer effect, we did not find a significant transfer effect for the explicit group, $M_d = -1.60$, 95% CI [−6.25, 3.05], $t(92) = -0.68$, $p = .497$, $d = -0.02$, 95% CI [−0.17, 0.12], but did find a significant transfer effect for the implicit group, $M_d = 8.16$, 95% CI [4.30, 12.01], $t(98) = 4.20$, $p < .001$, $d = 0.12$, 95% CI [−0.01, 0.25]. Additionally, the transfer effect was significantly smaller for the explicit versus implicit conditions, $\Delta M = -9.75$, 95% CI [−15.73, −3.78], $t(190) = -3.22$, $p = .002$, $d = -0.47$, 95% CI [−0.75, −0.18].

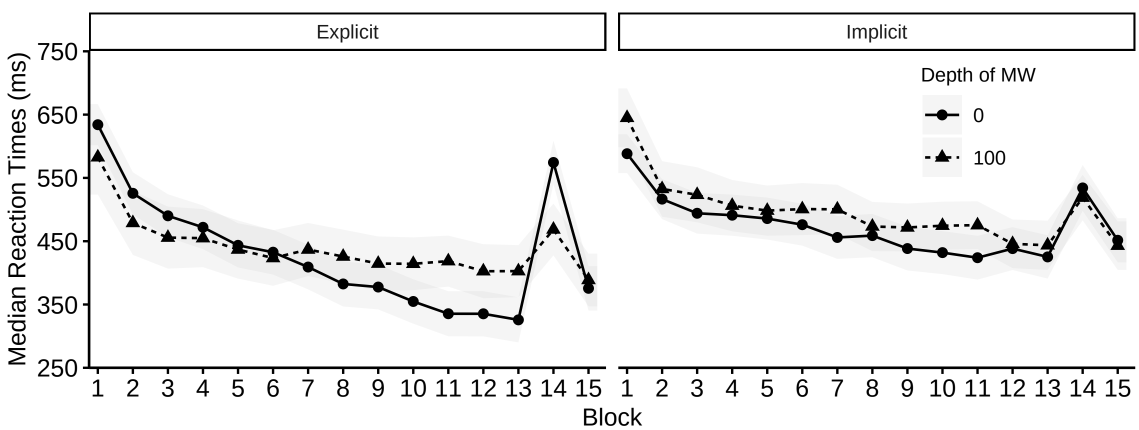

Figure 4. Results from the linear mixed model with depth of mind wandering, block, and awareness as fixed effects and subject as a random effect. Estimated median reaction times are plotted for 0 and 100 depth of mind wandering across awareness groups.

Mind wandering, awareness, and SRT performance

To determine the association between mind wandering, awareness, and SRT performance, we analyzed median reaction times using a linear mixed model with awareness condition (explicit versus implicit), depth of mind wandering, and block as fixed effects and subject as the random effect (see Figure 4). The full results of this analysis can be found in Appendix A. Of interest are the three-way interactions found in blocks 9 through 13. The model predicts larger practice and transfer effects for participants who report a lower depth of mind wandering than for participants who report mind wandering–but only in the explicit condition.

To further corroborate these results, we also analyzed the data using two linear regression models (see Figure 5), followed-up with Pearson correlations. In the first, we included depth of mind wandering and awareness condition as explanatory variables and the practice effect as the dependent variable. Here, we find a significant interaction between depth of mind wandering and condition, $b = 2.59$, 95% CI [0.75, 4.43], $t(182) = 2.78$, $p = .006$, such that mind wandering was negatively associated with practice effects in the explicit ($r = -.23$, 95% CI [$-.42$, $-.02$], $t(85) = -2.22$, $p = .029$), but not implicit condition ($r = .15$, 95% CI [$-.05$, .34], $t(97) = 1.50$, $p = .137$).

In the second analysis, we included depth of mind wandering and condition as explanatory variables and the transfer effect as the dependent variable. Here again, find a significant interaction between depth of mind wandering and condition, $b = 1.89$, 95% CI [0.51, 3.27], $t(182) = 2.71$, $p = .007$. Like the first analysis, we find a negative association between mind wandering and transfer effects in the explicit ($r = -.31$, 95% CI [$-.49$, $-.11$], $t(85) = -3.00$, $p = .004$), but not implicit condition ($r = -.08$, 95% CI [$-.27$, .12], $t(97) = -0.79$, $p = .431$).

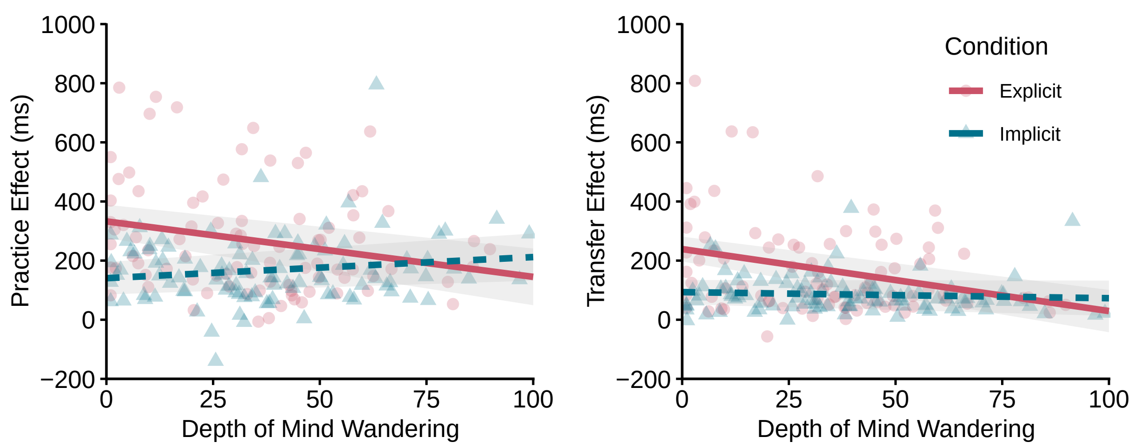

Figure 5. Results from the linear regression models plotted over participant data. Practice effects are plotted against depth of mind wandering (left) and transfer effects are plotted against depth of mind wandering (right).

Discussion

The present work had two aims: First, to determine whether there is a relationship between task automatization and mind wandering, and second, to determine whether mind wandering impedes implicit learning. To that end, we had participants complete a serial reaction time task using a 10-element repeating sequence (e.g., Pasquel et al.). One group was made aware of the repeating sequence (i.e., the "explicit" group) and the other was not (i.e., the "implicit" group). Participants practiced the sequence for 13 blocks at which point they were presented the reverse sequence for one block (block 14) before returning to the practice sequence for the final block (block 15). After each block of trials, we presented participants with a thought probe to gauge their depth of mind wandering and at the end of the experiment we assessed their awareness of the repeating sequence using two sequence generation tasks.

First, looking at the inclusion generation task we found that both groups could produce training sequence triplets and refrain from producing reverse sequence triplets. However, the explicit group outperformed the implicit group in both cases. More importantly, only participants in the explicit group could produce the reverse sequence triplets above chance. Taken together, the results of the two generation tasks suggest that the knowledge acquired by the explicit group was indeed more explicit in that they were better able to mentally reconstruct the training sequence and even reverse it.

In the serial reaction time task, we found that performance generally improved for both groups during the practice phase, while at the same time, depth of mind wandering increased. This provides novel evidence in favor of the task-automatization account: as the task became automated, participants engaged in more mind wandering. Additionally, this suggests that time-on-task effects cannot solely be explained by participants inferring their depth of mind wandering from their performance (e.g., Helton, 2018), as here we see performance steadily improving concurrently with increases in mind wandering. Though of course, this does not rule out the possibility that performance can influence thought probe responses–an issue we will return to shortly.

We also examined the association between mind wandering, learning, and awareness. Here, we found that depth of mind wandering was indeed associated with learning for the explicit group in that lower rates of mind wandering were associated with higher learning rates (as indexed by both practice and transfer effects). However, this was not the case for the implicit group, where we found no association between learning rates and mind wandering. This result is inconsistent with the work by Franklin et al., who did find that implicit sequence learning was negatively associated with mind wandering. Perhaps the simplest explanation for this inconsistency is that participants developed explicit knowledge in the Franklin et al. study (as the authors suggest is a possibility). Franklin et al. did not include an intentional learning condition and employed less than ideal awareness measures (Pasquali et al., 2019). Therefore, the current study provides a better test of implicit versus explicit learning effects. Another possibility lies in the structure of their task. They consistently alternated between the practice sequence and random sequences throughout the entire task. As we discuss in more detail below, the sudden and constant changes in task difficulty might have unforeseen consequences on self-reports of mind wandering.

Finally, we turn to a puzzling, yet potentially interesting, result: participants in the implicit group show a sharp increase in their reports of mind wandering following the reverse block and decreasing again following the final block. This contrasts with the explicit group who show no differences in their mind wandering across the three final blocks. One possibility is that the sudden increase in task difficulty did indeed cause more mind wandering–though, people often report *less* not *more* mind wandering in more difficult tasks. Another possibility is that participants inferred from the sudden decrease in performance that they had been mind wandering (e.g., Head & Helton, 2018). However, both the explicit and implicit groups see the same change in difficulty and the change in performance was more dramatic for the explicit group. If either of these explanations alone could account for this effect, we would expect to see it for both groups and perhaps an even larger change for the explicit group.

Here, we propose an alternative explanation Whittlesea et al. referred to as the "discrepancy-attribution hypothesis" (Whittlesea, 2002; Whittlesea & Williams, 2000, 2001). Much research has shown how people heuristically shape their subjective experiences (e.g., Kahneman & Tversky, 1973; Nisbett & Ross, 1980; Schachter & Singer, 1962). Based on this view, Whittlesea et al. argued that while people are engaged in the production of perceptual, cognitive and response, they are also involved in the evaluation of these production processes. In part, they evaluate the discrepancy between their current experience and what they could normatively expect given the context; it is these discrepancy-attributions that give rise to our subjective experiences (e.g., liking, knowing, familiarity). For instance, many have argued that processing fluency evokes a feeling of familiarity and is used as a heuristic to make recognition judgments (e.g., Brown & Marsh, 2009; Westerman, 2008; Whittlesea, 1993). Whittlesea et al., however, have shown convincingly that feelings of familiarity are not induced by processing fluency per se, but by the discrepancy in fluency unconsciously attributed to a previous experience (e.g., Whittlesea & Williams, 2000).

We suspect a similar process may underlie self-reports or "feelings" of mind wandering. People might use heuristics, such as a performance heuristic, to determine whether they had just been mind wandering. Of course, performance may fluctuate for many other reasons, such that, given the context, we develop normative expectations. Nonetheless, when there is a discrepancy between our actual performance and our normative expectations, we may unconsciously attribute the decrease in performance to an inattentional state such as mind wandering. This would explain why we only see the increase in mind wandering for the implicit group and not the explicit group. The implicit group was unaware of the repeating sequence and therefore unaware that the task had changed. The explicit group, however, was made aware of the repeating sequence and were likely aware that the task had changed. Whereas the explicit group could correctly attribute their sudden drop in performance to a shift in the task (i.e., no discrepancy), the implicit group could not; thus, the discrepancy is attributed to a prior inattentive state and creates a feeling of wandering mind.

Applying the discrepancy-attribution hypothesis to mind wandering raises a number of interesting questions. To start, what are the heuristics that evoke feelings of mind wandering? We have proposed a performance heuristic, but there may be others. For example, if there is a memory discrepancy for a prior experience, it may also evoke feelings of inattention or mind wandering. Or perhaps a discrepancy in our ability to detect environmental changes could evoke feelings of mind wandering. Another interesting question is whether people use discrepancy shifts to monitor their attentional states. That is, if a discrepancy creates a feeling of mind wandering, it could serve as an informative signal to reorient back to the focal task.

From a methodological point of view, it is especially important to understand whether the tasks we use influence feelings of mind wandering are especially important. We expect people, in general, can reliably attribute feelings of mind wandering to a mind wandering episode (i.e., task-unrelated thoughts, perceptual decoupling, etc.). Nevertheless, heuristics are prone to error and some laboratory tasks, as we have shown here, can inadvertently increase or decrease the feeling of mind wandering due to task-specific parameters such as performance feedback or task (un)awareness. Further work is needed to better identify how and when changes in task criteria that may or may not affect feelings of mind wandering.

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Appendix A

Linear Mixed Model Results

	Median Reaction Times		
Predictors	Estimates	95% CI	p-value
(Intercept)	634.05	[601.48, 666.62]	< 0.001
Condition [implicit]	−45.83	[−90.60, −1.05]	0.045
MW	−0.51	[−1.12, 0.09]	0.097
Block [2]	−108.39	[−133.09, −83.68]	< 0.001
Block [3]	−143.93	[−169.55, −118.30]	< 0.001
Block [4]	−162.09	[−188.33, −135.85]	< 0.001
Block [5]	−190.57	[−217.42, −163.73]	< 0.001
Block [6]	−201.43	[−228.84, −174.02]	< 0.001
Block [7]	−224.86	[−252.20, −197.52]	< 0.001
Block [8]	−251.57	[−279.35, −223.80]	< 0.001
Block [9]	−256.49	[−283.94, −229.03]	< 0.001
Block [10]	−279.26	[−306.39, −252.12]	< 0.001
Block [11]	−298.64	[−326.44, −270.84]	< 0.001
Block [12]	−298.72	[−326.66, −270.79]	< 0.001
Block [13]	−308.31	[−336.18, −280.45]	< 0.001
Block [14]	−59.67	[−85.99, −33.34]	< 0.001
Block [15]	−258.50	[−285.67, −231.34]	< 0.001
Condition [implicit] * MW	1.08	[0.31, 1.85]	0.006
Condition [implicit] *Block [2]	36.64	[2.45, 70.84]	0.036
Condition [implicit] *Block [3]	49.83	[14.50, 85.16]	0.006
Condition [implicit] *Block [4]	64.97	[28.87, 101.06]	< 0.001
Condition [implicit] *Block [5]	88.10	[51.01, 125.20]	< 0.001
Condition [implicit] *Block [6]	89.33	[51.84, 126.83]	< 0.001
Condition [implicit] *Block [7]	92.55	[54.58, 130.53]	< 0.001
Condition [implicit] *Block [8]	122.21	[83.59, 160.82]	< 0.001
Condition [implicit] *Block [9]	106.67	[67.84, 145.50]	< 0.001
Condition [implicit] *Block [10]	123.02	[84.99, 161.04]	< 0.001
Condition [implicit] *Block [11]	134.34	[95.25, 173.42]	< 0.001
Condition [implicit] *Block [12]	148.83	[110.28, 187.38]	< 0.001
Condition [implicit] *Block [13]	145.29	[106.42, 184.15]	< 0.001
Condition [implicit] *Block [14]	5.62	[−34.02, 45.26]	0.781
Condition [implicit] *Block [15]	121.76	[82.82, 160.69]	< 0.001
MW * Block [2]	0.05	[−0.73, 0.82]	0.907
MW * Block [3]	0.17	[−0.61, 0.95]	0.669
MW * Block [4]	0.34	[−0.42, 1.11]	0.380
MW * Block [5]	0.45	[−0.33, 1.22]	0.257
MW * Block [6]	0.42	[−0.34, 1.19]	0.279
MW * Block [7]	0.79	[0.04, 1.54]	0.038
MW * Block [8]	0.95	[0.19, 1.70]	0.014
MW * Block [9]	0.89	[0.13, 1.64]	0.022

Linear Mixed Model Results

	Median Reaction Times		
Predictors	Estimates	95% CI	p-value
MW * Block [10]	1.11	[0.37, 1.85]	0.003
MW * Block [11]	1.35	[0.61, 2.09]	$<$ 0.001
MW * Block [12]	1.19	[0.42, 1.95]	0.002
MW * Block [13]	1.28	[0.54, 2.03]	0.001
MW * Block [14]	−0.54	[−1.28, 0.19]	0.144
MW * Block [15]	0.65	[−0.10, 1.39]	0.088
(Condition [implicit] * MW) * Block [2]	−0.45	[−1.45, 0.54]	0.373
(Condition [implicit] * MW) * Block [3]	−0.45	[−1.45, 0.56]	0.384
(Condition [implicit] * MW) * Block [4]	−0.76	[−1.74, 0.22]	0.128
(Condition [implicit] * MW) * Block [5]	−0.89	[−1.87, 0.10]	0.077
(Condition [implicit] * MW) * Block [6]	−0.74	[−1.73, 0.24]	0.139
(Condition [implicit] * MW) * Block [7]	−0.91	[−1.88, 0.05]	0.064
(Condition [implicit] * MW) * Block [8]	−1.37	[−2.35, −0.40]	0.006
(Condition [implicit] * MW) * Block [9]	−1.12	[−2.09, −0.14]	0.024
(Condition [implicit] * MW) * Block [10]	−1.25	[−2.21, −0.29]	0.011
(Condition [implicit] * MW) * Block [11]	−1.40	[−2.36, −0.44]	0.004
(Condition [implicit] * MW) * Block [12]	−1.68	[−2.66, −0.70]	0.001
(Condition [implicit] * MW) * Block [13]	−1.67	[−2.64, −0.69]	0.001
(Condition [implicit] * MW) * Block [14]	−0.18	[−1.14, 0.78]	0.718
(Condition [implicit] * MW) * Block [15]	−1.30	[−2.27, −0.32]	0.009
Random Effects			
σ^2	4002.40		
$\tau_{00 Subject}$	17 535.37		
ICC	0.81		
$N_{Subject}$	186.00		
Observations	2790.00		
Marginal R^2 / Conditional R^2	0.16/0.84		