Understanding the behavioral and neurocognitive relation between mind wandering and learning

Judy Xu

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ABSTRACT

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In the last decade, tremendous advances have been made in the effort to understand mind wandering, yet many questions remain unanswered. Chief among them is how mind wandering relates to learning. Insofar as mind wandering has been linked to poor learning, finding ways to reduce the propensity to mind wander could potentially improve learning. Two experiments were conducted to examine this. The first experiment evaluated how difficulty of the to-be-learned materials affected one's tendency to mind wander and revealed that people mind wandered when there was a mismatch between their level of expertise and the difficulty of materials studied. The second experiment compared whether participants were more likely to mind wander in blocked or interleaved conditions and showed that participants were more likely to mind wander when materials were presented in a blocked fashion. Together, these results indicate that techniques such as studying materials specific to one's own level of mastery or changing the way in which one studies might reduce mind wandering and improve learning.

Of equal importance is the question of what happens on in the brain when a person mind wanders. While the effect of mind wandering on early sensory processing is known, the impact it has on learning-related processing is not. In two event-related potential (ERP) experiments, participants were asked to report whether they were mind wandering or not while studying materials they were later tested on. Analyses revealed that elaborative semantic processing – indexed by a late, sustained slow wave that was maximal at posterior parietal electrode sites – was attenuated when participants mind wandered. Crucially, the pattern when people were on

task rather than mind wandering was similar to the subsequent memory effect previously reported by other memory researchers, suggesting that mind wandering disrupts the deep level of processing required for learning.

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Note

Parts of the research presented here are excerpted from my own previously published work, i.e. journal articles.

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Dedication

I dedicate this culminating work to my undergraduate mentors, Drs. Julia Kam and Todd Handy. They were the first to spark my interest in mind wandering and train me in event-related potentials (ERPs). Without the opportunity to work closely alongside them, I would never have had the opportunity to gain a solid foundation in ERP, which has made this work possible.

On a personal note, I dedicate this work to my father, Wilsun Xu, my mother, Jenny Wang, and my brother, Colin Xu. This endeavor would not have been possible without their unconditional and unwavering support.

Introduction

Mind wandering refers to the mental phenomena where one's thoughts become disconnected from the task at hand and instead become focused on internal milieu (Smallwood & Schooler, 2006, 2015). From mindless reading to imagining a night out, mind wandering is characterized by the decoupling of thought from the present task onto internal mental events (Smallwood, 2013; Smallwood & Schooler, 2006). Imaging studies linking mind wandering to default mode network activity (e.g., Christoff, Gordon, Smallwood, Smith, & Schooler, 2009; Fox, Spreng, Ellamil, Andrew-Hanna, & Christoff, 2015; Mason, Norton, Van Horn, Wegner, Grafton, & Macrae, 2007; Stawarczyk, Majerus, Maquet, & D'Argembeau, 2011), support the idea that mind wandering is associated to disengagement from the external environment (Schooler, Smallwood, Christoff, Handy Reichle, & Sayette, 2011). Unfortunately, people are not always aware when their thoughts drift off, as the propensity to do so is spontaneous and often occurs without awareness (Christoff, 2012; Christoff, Gordon, Smallwood, Smith, & Schooler, 2009). Worse yet, in daily life, one's mind could be engaged in off-task thinking up to 50% of the time (Killingsworth & Gilbert, 2010), and it is thought to be very difficult to prevent it from happening.

Often, in mind wandering experiments, participants are asked to perform some task, such as the go no-go (e.g., Carriere, Cheyne, Solman, & Smilek, 2010; Jackson & Balota, 2012; Kam et al., 2011; McVay, Meier, Touron, & Kane, 2013; Smallwood et al., 2004; Smallwood, Beach, Schooler, & Handy, 2008; Zavagnin, Borella, & De Beni, 2014) or read a piece of text (e.g., Feng, D'Mello, & Graesser, 2013; Franklin, Smallwood, & Schooler, 2011; Reichle, Reineberg, & Schooler, 2010; Smallwood, 2011), and are intermittently 'probed' or interrupted and asked to report whether they were mind wandering or not. While there are some suggestions that mind wandering may be beneficial for creativity (Baird et al., 2012; Singer, 1975) or memory for future events (Mason, Bar, & Macrae, 2007; Mason & Reinholtz, 2015), there is a much larger literature associating mind wandering with poorer outcomes on a variety of metrics including executive functions (Kam & Handy, 2014), online motor control (Kam et al., 2012), driving (Galéra et al., 2012; He, Becic, Lee, & McCarley, 2011), and reading comprehension (Feng et al., 2013; Foulsham, Farley, & Kingstone, 2013; Reichle et al., 2010; Smallwood, 2011; Unsworth & McMillan, 2013). Most importantly, though, I argue, is the relation that mind wandering has on learning and memory. Insofar as one's attention is not focused on studying, learning is also expected to suffer.

Indeed, this relation of mind wandering and poorer learning has been found in the literature (e.g., Farley, Risko, & Kingstone, 2013; Lindquist & McLean, 2011; Metcalfe & Xu, 2016; Risko, Buchanan, Medimorec, & Kingstone, 2013; Smallwood, Fishman, & Schooler, 2007; Xu & Metcalfe, 2016). Mind wandering has been linked to impaired reading comprehension (Broadway, Franklin, & Schooler, 2015; Feng et al., 2013; Franklin et al., 2011; Reichle et al., 2010; Smallwood, 2011), worse knowledge retention (Farley et al., 2013; Thomson et al., 2014), poorer memory for online lectures (Spzunar, Khan, & Schacter, 2013), lower exam and SAT scores (Lindquist & McLean, 2011; Unsworth, McMillan, Brewer, & Spillers, 2012), and diminished recall (Metcalfe & Xu, 2016; Smallwood, McSpadden, & Schooler, 2007; Xu & Metcalfe, 2016). When we disengage from tasks requiring high levels of processing – e.g., reading or word encoding – our ability to process and perform the task worsens (Feng et al., 2013; Foulsham et al., 2013; Smallwood et al., 2003). Furthermore, performance decrements were specific to the periods of offline thinking: participants who reported mind wandering when reading specific passages also recalled less when asked about those passages

(Smallwood, McSpadden, & Schooler, 2008). This selectivity, such that only learning of the to-be-learned materials to which a person reports mind wandering to is hindered, also exists when studying English-Spanish word or image-word pairs (Metcalfe & Xu, 2016; Xu & Metcalfe, 2016). Simply put, mind wandering appears to pose a serious threat to learning, making it crucial to understand what might drive one's mind to go offline, and how this might be prevented.

While there are indications that interventions such as intermittent testing (Jing, Szpunar, & Schacter, 2016; Szpunar, 2017; Szpunar, Khan, & Schacter, 2013; Szpunar, Moulton, & Schacter, 2013) or mindfulness training (Mrazek, Franklin, Phillips, Baird, & Schooler, 2013; Schooler et al., 2014; Xu, Purdon, Seli, & Smilek, 2017) might reduce the predisposition to mind wander, there is still much to be explored within the context of mind wandering and learning. Given these problems, my dissertation attempts to address two questions. First, are there ways in which we can minimize one's proclivity to mind wander in an attempt to boost learning? And second, while mind wandering is linked to default network activation more generally, what are the neurocognitive consequences when mind wandering, specific to learning?

How can we reduce mind wandering?

Considerable research suggests that factors such as boredom and fatigue (Smallwood & Schooler, 2006) as well as negative affect (Killingsworth & Gilbert, 2010) are correlated with increased propensity to mind wander in daily life. Data from Risko, Anderson, Sarwal, Engelhardt, and Kingstone (2012) showed that students mind wandered more and recalled less during the second half of an online lecture, as opposed to the first half. As people spend more time on a task, fatigue and boredom increase, making it more likely for one's mind to drift off (McVay & Kane, 2009; Metcalfe & Xu, 2016; Smallwood et al., 2003; Smallwood, Riby, Heim, & Davies, 2006; Xu & Metcalfe; 2016). Work on individual differences also suggests that motivation and interest alter one's tendency to mind wander (Antrobus, Singer, & Greenberg, 1966; Grodsky & Giambra, 1990-91; Jackson & Balota, 2012; Krawietz, Tamplin, Radvansky, 2012; Seli, Cheyne, Xu, Purdon, & Smilek, 2015; Unsworth et al., 2012; Unsworth & McMillan, 2013). For example, Unsworth and McMillan (2013) proposed a model in which interest predicted motivation, and in turn predicted mind wandering. Thus, fatigue and boredom appear to increase the proclivity to mind wander, whereas increased interest may keep a person on-task.

Importantly, the finding that people who report being more interested tend not to mind wander (e.g., Unsworth & McMillan, 2013) suggests that if it were possible to experimentally manipulate interest, it might affect one's proclivity to mind wander. The Region of Proximal Learning (RPL) model, which will be discussed in a moment, proposes that if the difficulty of the task is calibrated to the knowledge state of the learners, their interest can be elicited. Therefore, individually calibrated level of task difficulty might be one such way to investigate whether studying in one's own RPL might reduce mind wandering.

The Region of Proximal Learning Model. According to the RPL framework, people learn best and are most engaged when performing tasks in which difficulty is titrated to their own ability and expertise level (Metcalfe, 2009, 2011; Metcalfe & Kornell, 2005). People become bored from the lack of challenge in very easy tasks. At the other extreme, exceedingly difficult tasks can be frustrating and tedious. Thus, people should spend more time and effort on tasks in their own RPL. The idea of tasks "just right" is similar to previous theories of human instruction and learning (e.g., Atkinson, 1972; Berlyne, 1978; Piaget, 1952; Vygotsky, 1987), which have proposed that people focus on materials most amenable to being mastered. An individual's RPL consists of items just beyond the learner's mastery, i.e. the easiest as yet unmastered materials. On the other hand, both already mastered and more difficult items are outside RPL.

The RPL framework is compatible with the work of Berlyne (1978), who investigated the relation between curiosity and stimulus complexity. Arousal, as measured by pupil dilation and skin conductance, was increased when people looked at slightly asymmetric patterns (Berlyne, 1978). In addition, people were more curious and spent a longer time staring at those slightly asymmetric images than at either very simple, predictable, symmetric images (i.e., too easy) or complex and unpredictable images (i.e., too difficult). Materials in one's own RPL are analogous to Berlyne's slightly asymmetric patterns as they would be slightly beyond an individual's current grasp and should, therefore, elicit curiosity when studied.

Experimental data on study choice and time allocation have shown that people tend to select and focus on studying items inside their own RPL (e.g., Metcalfe, 2002; Son & Metcalfe, 2000). For instance, participants often select the easiest as yet unlearned items to study (Kornell & Flanagan, 2014; Kornell & Metcalfe, 2006; Metcalfe, 2002, 2009; Metcalfe & Kornell, 2003, 2005; Thiede & Dunlosky, 1999). Kornell and Metcalfe (2006) found that participants learned more when they were forced to study RPL materials, as opposed to non-RPL materials. Despite having the same amount of study time, participants recalled fewer non-RPL items when assigned to study them. These findings in support of RPL highlight the importance of focusing on individual-appropriate tasks and materials.

As learning progresses, the particular items occupying an individual's RPL change. Metcalfe (2002) showed that college students initially focused on items of medium difficulty, turning to more difficult items only when study time was increased. Another study by Price and Murray (2012) had naïve Chinese speakers select Chinese characters of varying difficulty for study. Initially, participants chose to study the easiest Chinese characters, but over time they began selecting characters of medium difficulty, suggesting that they had learned the easier alternatives (Price & Murray, 2012). This transition towards more difficult materials arguably occurs after an individual has mastered the easier materials. Thus, RPL is constantly adjusted to fit the individual's current level of learning and differs among individuals.

Insofar as individuals differ in their knowledge and expertise, each person's optimum study choice of material difficulty, which is based on that person's RPL, is expected to differ. An expert has the correct schemas and knowledge to master more difficult tasks and materials than does a novice. Tasks and materials inside the expert's RPL are, hence, more difficult than those within the RPL of a novice. Metcalfe (2002) showed that items occupying the RPL of fluent Spanish speakers were more difficult than the items in the RPL of novice Spanish speakers. Similarly, concepts and information occupying the RPL of top-performing students would be expected to be more difficult than those in the RPL of students who have yet to grasp the basics.

If people are interested and motivated to study items in their own RPL, which may shift over the course of learning, it would be reasonable to expect that (1) people would mind wander when materials are outside their own RPL, (2) as one's own RPL shifts, so too would the materials which elicit mind wandering, and (3) the materials one person to mind wanders on will differ from the materials which another person mind wanders on. Chapter 1 uses the RPL model to test these hypotheses and provide a possible explanation for people's tendency to mind wander during learning.

Of course, it is always possible that despite one's interest in the material, mind wandering still occurs. Why might this be the case? As mentioned previously, fatigue and boredom are factors associated with the tendency to drift off-task. Aside from material difficulty, as measured by RPL, another factor that may contribute to the tendency to drift off-task when learning may be the way in which people study.

Blocked vs. interleaved practice. Considerable research suggests that people often believe and feel they learn better when they rehearse the same and/or similar materials over and over again, e.g., blocking (or massing), compared to if materials are mixed or interleaved across different categories (Kornell & Bjork, 2008; Kornell, Castel, Eich, & Bjork, 2010; Yan, Bjork, & Bjork, 2016; Zulkiply & Burt, 2013). However, this is belied by findings indicating that interleaving may actually result in better learning than blocking (Kornell & Bjork, 2008; Kornell, Castel, Eich & Bjork, 2010; Metcalfe & Xu, 2016; Verkoeijen, & Bouwmeester, 2014; Vlach, Sandhofer, & Kornell, 2008; Wahlheim, Dunlosky, & Jacoby, 2011). One explanation this so-called interleaving effect in item recall or recognition paradigms posits that that interleaving recruits more attention (and hence encoding strength) than blocking (Greeno, 1970, Hintzman, 1974; Pavlik & Anderson, 2005). Given this, might these purported attentional differences between the blocked and interleaved conditions be manifested in differences in mind wandering?

The idea that was tested is that when many exemplars of a particular category – for example, works of art by a particular artist – are grouped together, as in a blocked situation, people's attention may tend to lapse, resulting in mind wandering. On the other hand, when the exemplars are interleaved with the exemplars of other artists, attention may be sustained. It is possible, of course, that when people have to flit from artist to artist, their attention may wander: it is not empirically known whether mind wandering occurs more in the interleaved or the blocked condition. The attentional explanation of the interleaving effect can be evaluated by assessing mind wandering, and would suggest that there would be more mind wandering, and that mind wandering would be linked to worse learning, in the blocked condition.

The predictions – that learning should be better when one is *not* mind wandering, and that one may mind wander more under blocked than interleaved conditions – are addressed in Chapter 2.

Neurocognitive effects of mind wandering during learning

While many of the behavioral consequences of mind wandering are understood, the neurocognitive mechanism which underlies the failure to learn is still not well understood. As argued in Craik and Lockhart's (1972) seminal 'levels of processing' paper, memory performance is enhanced by deep (i.e., semantically) processing of the to-be-remembered information. If a person mind wanders while attempting to learn, a reasonable expectation might be that they would fail to engage in the deep semantic processing necessary to encode materials into memory. In support of this view, Thomson, Smilek, and Besner (2014) found a negative association between mind wandering and recognition of items in a deep semantic encoding condition, in which participants judged whether presented words represented items larger or smaller than the computer monitor. They found no deficit in memory as a function of mind wandering in the shallow-encoding condition, in which the participants judged whether words were in upper or lower case (Thomson et al., 2014). This result might have occurred either because the neural networks involved in deep semantic processing were disengaged, or because they were engaged but not directed at the task at hand.

Research with functional magnetic resonance imaging (fMRI) has shown that a subset of brain regions known as the default mode network is active during mind wandering (Christoff et al., 2009; Fox et al., 2015; Mason et al., 2007; Stawarczyk et al., 2011). Insofar as default mode network activity has been associated with autobiographical memory and other higher-order cognitive functions (see Buckner, Andrews-Hanna, & Schacter, 2008 for review), this activation would suggest that a person may be engaged in deep, memory-related, thought during mind wandering. However, whether this activation indicates that the learner is deeply processing *task-relevant* (e.g., the current to-be-learned material), or irrelevant (e.g., something other than the task) information during mind wandering is difficult to determine given the poor temporal resolution of fMRI. Instead, temporally precise tools such as electroencephalography (EEG) or magnetoencephalography (MEG) would be required to reconcile the finding of purportedly deep memory-related processing evidenced by the fMRI findings, with the concurrent deficit in memory exhibited by the behavioral data.

Research conducted with event-related potentials (ERP) has suggested that when an individual is in a mind-wandering state, they exhibit diminished processing of the external world, resulting in deficits in early attentional processing (e.g., Braboszcz & Delorme, 2011; Broadway et al., 2015; Kam, Dao, Farley, Fitzpatrick, Smallwood, Schooler, & Handy, 2011; Kam, Dao, Stanciulescu, Tildesley, & Handy, 2013; O'Connell, Docktree, Robertson, Bellgrove, Foxe, & Kelly, 2009). This has been exemplified by work showing decrements in visual processing, indexed by the P1 ERP component at parieto-occipital electrodes such as PO3, PO4, and Oz, which overlie the occipital cortex (e.g., Kam et al., 2011). Researchers have also found that mind wandering attenuates the P3 component, an ERP index of higher-order cognitive functions such as decision making (Barron, Riby, Greer, & Smallwood, 2011; Kam, Xu, & Handy, 2014; Riby, Smallwood, & Gunn, 2008; Smallwood et al., 2008). Attenuation of this component might be expected to be related to learning. However, these studies have employed tasks that do not involve learning, such as the oddball task (Barron et al., 2011), the sustained attention to response task, a variant of a go no-go task (Smallwood et al., 2008), and emotional image categorization (Kam et al., 2014). As such, they did not assess the question of learning and memory.

Only one experiment (Riby et al., 2008) has examined mind wandering and episodic recollection using ERPs. Participants were presented with words and pictures within a colored frame and instructed to remember the stimuli by generating mental images of the colored frame and word (or picture). At test, participants were shown old and new frame-word pairings and were asked to identify whether a particular colored frame had been paired with a particular word. The authors divided their participants into those who had a high tendency to mind wander and those who had a low tendency to mind wander according to scores on the Dundee Stress State Questionnaire (Riby et al., 2008). Although there was no difference in memory, there were differences in ERPs. The results also indicated a larger central-negativity from 500-900 ms and smaller left parietal effects, e.g., a smaller difference between correct recognition of previously seen materials and new materials, from 900-1500 ms for high mind wandering participants during recall. The authors argued that because high mind-wandering participants lacked highly detailed episodic memories, as compared to those of the low mind-wandering group, they needed to recruit a non-“pure” recollection strategy (smaller left parietal effect) and utilized strategic monitoring processes (central-negativity) during recall (Riby et al., 2008). The purportedly different recall strategies were attributed to participants’ attention being decoupled from the task during encoding. While these results might suggest that mind wandering impacts deep task related processing, there are several problems with this straightforward interpretation. First, the study examined ERPs at test, rather than at encoding. Processing differences between the two groups at retrieval were taken as evidence for differences in recollection strategy, which were then used to infer behavior during encoding. Second, the effect of mind wandering was assessed using a between-participant comparison of high and low mind wanderers. Participants were never asked to report their attentional state *during* the task, making it difficult to draw inferences as to what transpired *within* an individual's brain during a mind wandering episode. The determination of the high and low mind wandering group was also not matched to task-specific rates of mind wandering. It would be better to evaluate stimulus-related ERPs during (and time-locked to) the encoding of individual to-be-remembered items. Furthermore, it would be better to evaluate mind wandering as compared to on-task states while the individual is doing the task, rather than asking for a retrospective global report later.

So what might the impact of mind wandering during learning look like with ERPs? One line of evidence comes from work on the subsequent memory or difference in memory (Dm) effect, which has shown that the neural signature of deep processing during encoding is different for items that are subsequently remembered or not remembered (Fabiani, Karis, & Donchin, 1990; Friedman, 1990; Friedman & Johnson, 2000; Friedman & Trott, 2000; Johnson, 1995; Paller, McCarthy, & Wood, 1988; Paller, Kutas, & Mayes, 1987, Sanquist, Rohrbaugh, Syndulko, & Lindsley, 1980). Paller, Kutas, and Mayes (1987) found that when ERPs at study were categorized on the basis of subsequent test performance, items that were subsequently remembered elicited larger ERPs from 400-800 ms than those that were forgotten. Interestingly, an ERP experiment showed that the late positivity ERP difference between recalled and unrecalled materials was larger than the difference between recognized and unrecognized materials (Paller et al., 1988). Because recall is more strategic than recognition requiring greater recollection-based processing, these differences suggest that the encoding-related ERPs might indicate the degree of deep or elaborative processing engaged in during encoding. The ERP differences associated with subsequent recall have generally occurred. as noted earlier, relatively late, from 400-800 ms (e.g., Paller et al., 1987), with little difference in earlier sensory processing, as indexed by components such as the P1. Thus, if mind wandering reduces task-relevant encoding, regardless of what else happens during mind wandering, the amplitude of the sustained late ERP component should be diminished during off-task thought. Chapters 3 and 4 attempt to elucidate the impact of mind wandering on learning-related processing using ERPs, test the prediction that mind wandering during learning is associated with reduced deep-level processing.

Together, Chapters 1 and 2 aim to uncover the causes of mind wandering in two different learning situations, and provide suggestions on how one might go about reducing their proclivity to drift off-task. On the other hand, the focus of Chapter 3 is on understanding the neurocognitive consequences of mind wandering on learning-related processes. Finally, Chapter 4 ties together the results from earlier chapters, simultaneously considering behavioral and electrophysiological data to provide a more holistic view of the effects of mind wandering on learning.

Chapter 1:

Mind wandering, Expertise, and Material Difficulty

This first chapter investigates how material difficulty and individual differences are related to mind wandering. More specifically, will studying materials at an appropriate level of difficulty with respect to an individual's capabilities, i.e., materials in one's own RPL, reduce mind wandering and lead to better learning?

As discussed previously, one's predisposition to mind wander is affected by a multitude of factors, such as motivation and interest (Antrobus et al., 1966; Grodsky & Giambra, 1990-91; Jackson & Balota, 2012; Krawietz et al., 2012; Seli et al., 2015; Unsworth et al., 2012; Unsworth & McMillan, 2013), and boredom and fatigue (Smallwood & Schooler, 2006). Specifically, people mind wander *less* when they find something motivating and interesting, and *more* when they are bored or fatigued. In learning contexts, the ideal candidates for study should therefore be materials which one is most interested in learning. How should one go about identifying these target materials?

One possibility arises from the Region of Proximal Learning or RPL framework suggests that people should focus on items just beyond their current level of expertise (e.g., Metcalfe, 2009). Notably, this model is compatible with work on curiosity, showing that people were more aroused by images that were not only more complex than simple, symmetric images, but also easier than unpredictable and chaotic images (Berlyne, 1978). Similar to Berlyne's slightly asymmetric patterns, as RPL items are neither too easy or too difficult, they should elicit higher levels of curiosity and interest when studied. It follows, then, that people should mind wander less when studying materials in their own RPL compared to materials which are too easy or too difficult.

In Experiments 1 and 2, participants were given a pretest in an attempt to determine which items were in RPL. Participants were then asked to study word pairs, blocked by whether they were: (a) very easy, (b) in RPL, or (c) too difficult, while being intermittently asked to report their attentional state as either mind wandering or on task. Participants were expected to mind wander less when studying materials in their own RPL, as opposed to when studying very easy or very difficult materials.

Experiment 1

In this experiment, participants took a pretest and provided judgments of learning (JOLs) on a series of English-Spanish word pairs. This pretest was done to enable the word pairs to be classified into those that were too easy, too difficult, or in RPL. Participants then studied the word pairs, blocked by whether they were easy, RPL, or difficult, and were probed, while doing so, to see if they were mind wandering. Participants then completed a final test. The prediction was that participants would learn a higher proportion of RPL word pairs than either the too difficult or too easy pairs. In addition, participants should also report less mind wandering when studying materials in RPL compared to when studying materials that were either too easy or too difficult. Finally, items ‘studied’ while people were mind wandering should be learned worse than those studied when they were on-task.

Method

Participants. 25 Columbia University undergraduates participated for partial course credit, but one was excluded for not understanding the task and two were excluded for not completing the experiment, resulting in 22 usable participants (13 females and 9 males; *M* = 20.14 years old, *SD* = 1.93). One participant reported being a native Spanish speaker and was included because RPL was computed to their expertise. Excluding this participant did not change the patterns in the data, however. The number of participants needed for this experiment was approximated from numbers in previous RPL experiments (e.g., Kornell & Metcalfe, 2006). All participants gave written consent and were treated in accordance with the ethical principles of the Psychonomics Society and Columbia University's Internal Review Board.

Materials. The materials used were 155 English-Spanish word pairs, 144 of which were taken from previous research (Metcalfe, 2002; Metcalfe & Kornell, 2003, 2005). The additional 11 Spanish-English pairs that were added were perfect conjugates, so participants without any Spanish background would be able to guess the translations and/or provide high JOLs. Word pairs varied in difficulty from perfect conjugates (e.g. "TAXI" and "TAXI") to medium items (e.g., "MUSIC HALL" and "VODEVIL") to very difficult pairs (e.g. "STAIN" and "CHAFARRINADA").

Design. A within-participant design was used. Difficulty– easy, RPL (medium), or difficult, which was determined by the pretest for each participant individually – was treated as if it were an independent variable. The duration of each study block was also manipulated. There were 4 duration levels (15, 30, 60, and 90s), one in each of the three difficulty levels. The duration was varied so that participants would not be able to anticipate the onset of the attentional probe during study, and collapsed across duration for the analysis. The dependent variables of interest were frequency of reported mind wandering, measured in the study phase, and learning, measured by proportion correct in the final test. There were a total of 12 blocks, 4 per difficulty level. Blocks were permuted such that each of the 3 Difficulties – easy, RPL (medium), and difficult – showed up in a randomized fashion every 3 blocks, but associated with different Durations. Each word pair was presented an average of 7.70 times over the course of the entire study period (SD_{easy} = 2.87; SD_{RPL} = 2.75; $SD_{difficult}$ = 2.80).

Procedure. This experiment had 3 parts: 1) pretest, 2) study phase, and 3) final test. The pretest enabled categorization of word pairs into easy, RPL (medium), and difficult categories for study. In the study phase, participants were asked to study the word pairs, blocked by Difficulty, while from time to time reporting whether they were on task or mind wandering. Finally, at the end of the experiment, participants were tested on their learning.

Pretest. Participants were instructed to provide Spanish translations for the 155 English words presented one at a time onscreen. They were then shown the correct translation. Whenever they provided either an incorrect or no translation, they were asked to make a JOL following the corrective feedback. Item presentation was randomized and participants had up to 25s to provide the translation for each item. Feedback in the form of the correct Spanish translation was given in either green when they were correct, or red when incorrect. JOLs were made on a slider scale ranging from “not at all learned” to “completely learned”. Strict scoring was used on the spelling of each response

Materials were sorted into 3 levels of Difficulty based on each participant's individual pretest response accuracy and JOLs: *easy* (close to accurate or accurate), *RPL* (inaccurate but high JOLs), and *difficult* (inaccurate and lowest JOLs). Thirty-five items were sorted into each level of Difficulty. 25 items at each difficulty level were presented for study, and the remaining 10 were used as unstudied control items on the final test. When participants did not have 35 items to which they had given the correct translation, pairs to which they had given wrong answers but with the highest JOLs were added to the easy condition. In total, 20.3 out of 35 word pairs had been correct on the pretest in the easy condition which meant that, unfortunately, quite a few of the easy items were not fully mastered, *a priori*.

Study phase. Participants were asked to study the English-Spanish word pairs, one at a time, with the English word on the top and the to-be-learned Spanish word on the bottom. Individual word pairs were presented sequentially on screen for 900ms, with a 100ms interstimulus interval (ISI). Participants were also instructed that they would be asked to report their attentional state as either *on-task* or *mind wandering* from time to time, when a probe appeared. Mind wandering was operationalized as "*when [one is] not paying attention to the task (i.e. learning the word pairs) or [when one was] thinking of something other than the task*." As noted above, pairs were blocked at time of presentation such that items solely within one difficulty level appeared together in sequence, followed by an attentional probe which could occur after 15, 30, 60, and 90 s of study at a particular difficulty level.

Probes were designed to imitate word pair presentation, but with the terms "MIND WANDERING" and "ON TASK" displayed instead of a word pair. Probes were shown for 900ms with a 100ms ISI repeatedly, while randomly alternating whether "MIND WANDERING" was at the top or bottom, until the participant provided his or her attentional report.

Final test. Participants were provided with each English term and asked to recall the Spanish translation. No feedback was given. A total of 105 cue words were presented, with 35 cues per difficulty level (25 studied and 10 unstudied). Presentation order was randomized and participants had up to 25s to provide a translation. Recall performance was strictly scored for accuracy. All experimental procedures were conducted using MATLAB 2013a and PSYCHTOOLBOX (Brainard, 1997; Kleiner, Brainard, & Pelli, 2007) on Macintosh computers.

Results

For all experiments, the criterion for significance was set at $p < .05$. Partial eta squared (η_p^2) was used as the measure of effect size for analysis of variance (ANOVA) data. Post hoc *t* tests were computed for follow-up comparisons on significant effects and the associated *p* values and 95% confidence intervals are directly reported. Cohen's *d* was used as a measure of effect size for the *t*-tests.

Final test performance. To ensure participants were performing the task, i.e., actually studying, final test performance between studied pairs and the unstudied controls was compared. There was an overall effect of studying, such that participants' test performance was significantly better on pairs they studied, $M = 0.47$, $SD = 0.13$, than on the unstudied control pairs, $M = 0.35$, $SD = 0.14$; $t(21) = 6.81$, $p < .001$; 95%CI [0.02, 0.08], $d = 1.46$. Note, though, 'unstudied' is something of a misnomer. Even items that were designated as 'unstudied' were given corrective feedback immediately following pretest response, so some learning could have been attributed to that single study opportunity.

There was a significant difference in final test performance among the studied items in the three difficulty levels, $F(2,42) = 226.29$, $p < .001$, $\eta_p^2 = 0.92$. Participants performed best on the easy pairs, then the RPL(medium) pairs, and worst on the difficult pairs, as in shown in Table 1. As noted previously, 58.3% of the easy pairs had been correct on the pretest, whereas none of either the RPL or the difficult pairs had been correct. If proportion correct on the final test minus proportion correct on the pretest is taken as the measure of learning, learning would then correspond to final test performance for the RPL and difficult word pairs. For easy items, though, the difference between final test and pretest performance is not the same as final test performance. With this difference as a measure of learning, a significant effect of Difficulty was found, $F(2,42) = 21.65$, $p < .001$, $\eta_p^2 = 0.51$. As is shown in Table 1.1, participants learned more RPL items ($M = .50$; $SD = .25$) than either easy items ($M = .27$; $SD = .25$), $t(21) = 2.49$, $p = .021$; 95%CI [0.04, 0.41], $d = 0.91$, or difficult items ($M = .05$; $SD = .07$), $t(21) = 9.24$, $p < .001$; 95%CI [0.35, 0.55], $d = 2.46$. They also learned significantly more easy word pairs than difficult word pairs, $t(21) = 3.87$, $p = .001$; 95%CI [0.10, 0.34], $d = 1.22$.

	Pretest	**Final Test**		**Learning**
		Unstudied	Studied	
Experiment 1				
Easy	.58 (.32)	.71 (.23)	.86 (.13)	.27 (.25)
RPL	0	.35 (.22)	.50 (.25)	.50 (.25)
Difficult	0	0 (.02)	.05 (.07)	.05 (.07)
Experiment 2				
Easy	1.00	.88 (.15)	.92 (.07)	---
RPL	0	.39 (.20)	.56 (.19)	.56 (.19)
Difficult	0	.02 (.07)	.06 (.09)	.06 (.09)

Table 1.1. Pretest and final test performance for Experiments 1 and 2

Pretest and final test performance means for categorized word pairs in Experiments 1 and 2. The standard deviation are in parentheses. Learning was calculated from taking the difference between final test and pretest performance on studied items. Learning was not calculated for the easy word pairs in Experiment 2, because items were sorted based on being accurate at pretest. In Experiment 2, there was 1 participant who only had 5 word pairs in their easy condition, but was included.

Mind wandering. Participants mind wandered an average of 0.36 of the time (SD = 0.15). There was a significant effect of Difficulty on mind wandering, $F(2,42) = 4.33$, $p = .02$,

η_p^2 = 0.17, as is shown in the left panel of Figure 1.1. Participants reported significantly more mind wandering when they were studying difficult items as compared to the RPL (medium) items, $t(21) = 2.66$, $p = .015$; 95%CI [0.05, 0.38], $d = 0.57$. There was no difference in rate of mind wandering when studying easy versus RPL items, $t(21) = 0.70$, $p = .49$; 95%CI [-0.18, 0.09], $d = 0.15$. There was a trend to mind wander less when studying easy items than when studying difficult items, $t(21) = 2.02$, $p = .06$; 95%CI [-0.01, 0.35], $d = 0.43$.

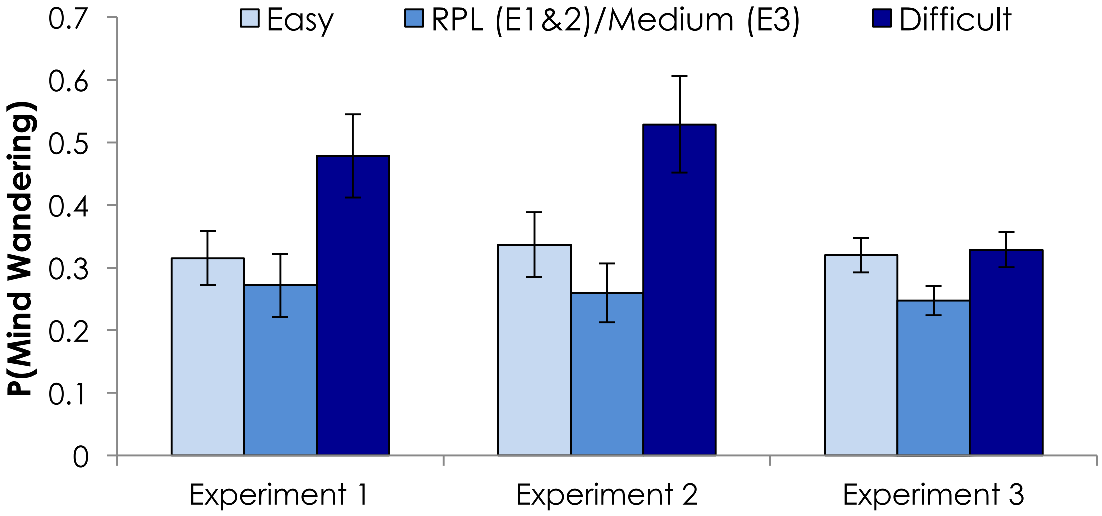

Figure 1.1. Mind wandering in Experiments 1, 2, and 3

Proportion (P) of mind wandering by Difficulty in Experiments 1, 2, and 3 with standard error bars.

Mind wandering and learning across participants. There was no correlation between participants' proportion of mind wandering in the experiment and their average test performance, $r = .17$, $t_r(20) = 0.75$, $p = .46$, 95%CI [-0.27, 0.55]. In this experiment, then, people who mind wandered a lot did not perform worse than those who rarely mind wandered.

Mind wandering and learning within participants. The data were divided into items that were presented just before people reported being on task or just before they reported that they were mind wandering. Although how far back in time the state reported at the time of the probe extends is not known precisely, previous studies have used time windows of approximately 9-12s when binning data based on attentional state (e.g., Braboszcz & Delorme, 2011; Kam et al., 2013; Kam et al., 2014). Using these guidelines, word pairs presented within the 10s preceding each attentional report were selected and used for analyses. Because many of the easy items were already learned, only RPL and difficult word pairs, which were unlearned at pretest, were included. As there were only four attentional reports per Difficulty condition, and they would sometimes all be in one state or the other, items in the RPL and difficult bins were collapsed. Because particular items were repeated (on average 7.7 times) in the experiment, some pairs ended up being included in both the mind wandering and the on-task condition in this analysis. Items were not weighted based on distance to probe. Performance on all items included in the 10s pre-probe interval were identified and the proportion correct at test was computed. If a particular item happened to occur twice or three times within a given interval, the item was still counted. In other cases, an item might be included in both the mind wandering and on task bins, and contributed to both the proportion correct for items presented before a mind wandering response, as well as the proportion correct for items presented before an on task response. Learning was significantly better for items that had been studied when participants reported that they had been on-task, $M = 0.34$, $SD = 0.17$, as compared to when they reported that they had been mind wandering, $M = 0.22$, $SD = 0.24$, $t(21) = 2.22$, $p = .038$; $d = 0.47$, 95% CI[0.01, 0.23].

Discussion

These results indicate that participants mind wandered less when studying items in their region of proximal learning as compared to when they were studying pairs of words that were very difficult. Participants' learning of materials 'studied' when mind wandering was also worse.

The findings of poorer performance *within* participants when mind wandering, and no correlation between mind wandering and performance do not necessary contradict. The cross-participant correlation analysis suffers from several problems, which was why a metric investigating at the effect of mind wandering on learning *within* each participant was computed. First, there is an insufficient number of participants, and therefore a lack of power (c.f., Cohen, 1992) to detect between-participants correlations. Second, attention fluctuates, such that a participant might have been focused at the beginning of each study block, but might have ended up mind wandering right before the probe appeared. This would have led to a weaker association between proportion mind wandering and overall performance.

In this experiment, there was no difference in reported mind wandering when studying RPL (medium) compared to easy items. However, because of the manner in which items were allocated to the easy condition, it is likely that a number of the nominally easy pairs might have been RPL items. The Region of Proximal Learning is thought to consist of materials that are close to being, but not quite mastered, whereas the 'too easy' items that are not in the RPL, are those that have already been fully mastered. Insofar as a number of easy items in Experiment 1 were not correct in the pretest, the lack of difference in mind wandering between the easy and the RPL items might have resulted because the easy items were not easy enough, that is, they were not completely mastered. Experiment 2 was conducted to replicate the previous findings and to address this issue.

Experiment 2

There were two main changes in Experiment 2. First, the criterion for an item to be considered to be “easy” was changed – only pairs of items that the participant got correct on the pretest were considered easy. Second, to obtain enough ‘easy’ items that people would answer correctly, the number of conjugates was increased.

Method

The method used was identical to Experiment 1, except for the details below.

Participants. A total of 26 Columbia University undergraduates (10 males and 16 females; *M* = 22.23 years old, *SD* = 6.88) participated for partial course credit. Two participants reported being native Spanish speakers, but because RPL was computed based on participants’ own prior learning, they were not eliminated from the data. Additional analyses computed without these individuals did not change the results.

Materials. An additional 35 perfect Spanish-English conjugates were added to previous set, for a total of 179 word pairs. This allowed participants to provide a larger number of accurate translations during pretest, yielding enough materials for an ‘easy’ category without having to include items on which people had been incorrect on the pretest.

Design. A within-participant design investigating the effect of item difficulty (easy, RPL, or difficult, as determined by the pretest) was used. The outcome measures of interest were (a) the proportion of mind wandering reported during the study phase and (b) the proportion correct on the final test. Duration of study block was, again, manipulated to have 4 different levels (15, 30, 60, 90s).

Procedure. Three changes were made to the procedure. First, participants only had 10s on the pretest and final test to provide a response. This was done so the experiment could be completed within an hour. Second, only pairs that participants got correct in the pretest were categorized as easy. Both RPL and difficult categories were comprised of 35 items each, 25 which were presented during the study phase and 10 of which were not included in the study phase. Participants had 25 easy word pairs to study (except for one participant who only provided five correct translations). An average of 8.52 (*SD* = 2.83) pairs were used as the control, non-studied easy condition, because not all participants provided up to 35 correct translations. Third, blocks in the study phase were counterbalanced using a Latin Square rather than randomly. In the whole experiment, word pairs were presented an average of 7.79 times each (*SD* = 3.18 times).

Results

Because of a programming error, final test data were lost for one participant. However, that person's data were included in the mind wandering results and the results did not change after analyzing the data without that participant's data.

Final Test Performance. Participants performed significantly better on pairs they had studied, *M* = 0.51, *SD* = 0.07, as compared to those they had not studied, *M* = 0.39, *SD* = 0.11; *t*(24) = 5.64, $p < .001$; 95%CI [0.07, 0.16], *d* = 1.13. As presented in Table 1.1, there was a main effect of Difficulty, such that proportion correct on the final test was highest on easy items (*M* = .91, *SD* = .06), followed by the RPL items (*M* = .51, *SD* = .18), and then the difficult items (*M* = .05, *SD* = .08), *F*(2,48) = 309.36, $p < .001$, $\eta_p^2 = 0.93$. Interestingly, people did not have perfect performance on the final test on the easy items, even though they had been correct on all those items at pretest. When they had no opportunity to study the easy items further their performance was .88; it was .92 when they had the opportunity to study.

Final test performance on studied word pairs was taken as an index of learning for the RPL and difficult word pairs, because all items in those categories had been incorrect on the pretest. Participants' learned significantly more RPL pairs ($M = .56$, $SD = .19$) than difficult pairs ($M = .06$, $SD = .09$), $t(24) = 11.74$, $p < .001$; 95%CI [0.41, 0.59], $d = 2.35$. A measure of learning could not be taken for easy items because they were correct on pretest.

Insofar as all of the items in the easy category had been correct on the pretest, the fact that performance was less than 1.0 on the final test provides a strong indication that some of those items had been correct, initially, because of guessing. It is impossible to determine how many were guesses, because final performance data for easy items are a mix of items that were learned *a priori*, items that were learned during the experiment, and items that were never learned but were correct guesses on the final test.

Mind wandering. The overall reported rate of mind wandering was 0.38 ($SD = 0.24$). Four participants did not report any mind wandering. There was an effect of Difficulty on the probability of mind wandering, $F(2,50) = 9.23$, $p < .001$, $\eta_p^2 = 0.27$ (see Figure 1.1, panel 2), such that participants mind wandered less when they were studying items in the RPL category as compared to when they were studying items the difficult category, $t(25) = 3.70$, $p = .001$; 95%CI [0.13, 0.40], $d = 0.73$. There was also a trend for people to mind wander less when they were studying RPL items than when they were studying the easy items, $t(25) = 1.78$, $p = .08$; 95%CI [-0.01, 0.17], $d = 0.35$. It is likely that this effect was not stronger because although an attempt was made to ensure that the easy pairs were fully learned *a priori*, it is impossible to ensure that people had fully mastered them. Participants mind wandered more when studying difficult pairs than easy pairs, $t(25) = 2.48$, $p = .02$; 95%CI [0.02, 0.35], $d = 0.49$.

Mind wandering and learning across participants. A correlation between overall mind wandering and average test performance was computed. there was a significant negative correlation, $r = -.46$, $t_r(23) = -2.47$, $p = .022$, 95%CI [-0.72, -0.08], such that participants who mind wandered more performed worse on the test.

Mind wandering and learning within participants. The proportion correct on final test was evaluated when people had mind wandered and when they had been on task, for the RPL and difficult items combined. As had been the case in Experiment 1, learning was better for items presented before 'on-task' reports, $M = 0.38$, $SD = 0.18$, than before 'mind wandering' reports, $M = 0.20$, $SD = 0.17$, $t(18) = 3.34$, $p = .004$; $d = 0.77$, 95% CI[0.07, 0.29].

Discussion

Consistent with Experiment 1, participants mind wandered more when studying difficult items as compared to those in their RPL. Caution should be used when interpreting the negative correlation found in Experiment 2 and lack of one in Experiment 1, due to both analyses being underpowered. However, along with the within-participant analyses, overall, this suggests that learning was adversely affected by mind wandering. Additionally, the data in this experiment suggest that studying items that are very easy might result in more mind wandering than studying items that are in one's own RPL.

Experiment 3

Previous research has shown that the materials that are in an individual's RPL differ based on the expertise of the learner (Metcalfe, 2002). For example, when people who spoke Spanish fluently chose items to study, they avoided the easiest items (since they already knew those items) and chose the difficult items. Novices, however, tended to choose the easier items over the more difficult ones. These choices suggested that the materials in the RPL of the more expert learners are normatively more difficult than the materials in the RPLs of the novices. Consequently, people with greater mastery of the materials in the present experiment – those people who exhibited higher performance levels – should show a similar result in terms of attentional state: they should mind wander more on easier items, and focus attention instead on more difficult items. In contrast, people with less knowledge of the materials might be more on-task on easier materials and tend to mind wander on the more difficult items.

To investigate this hypothesized difference, participants were presented with and asked to study word pairs that were blocked by difficulty. Two tests were included in this experiment – one in the middle and one at the end – to investigate changes in mastery over time. Low performers, as determined by proportion correct on these two tests, were expected to mind wander most when studying difficult items, because those materials would be furthest away from their RPL. In contrast, high performers should mind wander most when studying easy items and be more on task on materials of higher difficulty – those that posed just the right amount of challenge for them. Participants were also expected to mind wander more over time as they became fatigued.

Method

Participants. 89 Columbia University undergraduates participated for partial course credit or for $15 in cash, but 3 could not complete the task due to the computer error, resulting in 86 participants (31 males; *M* = 21.08 years old, *SD* = 4.27). To examine the relation between mind wandering and learning, and because this was an investigation of individual differences, the 85 participant criterion set by Cohen (1992) to look at medium-sized correlational effects was used to determine the sample size. One participant did not fill out the detailed demographic questionnaire, and six reported being native Spanish speakers. The native Spanish speakers were kept in the data. Analyses were also computed with these participants removed and did not change.

Materials. A list of 45 word pairs of widely varying difficulty based on the performance of participants in Experiments 1 and 2 was constructed. 15 of the pairs were very easy, 15 of medium difficulty, and 15 very difficult. No perfect Spanish-English conjugates were included in the present experiment. Because there might still be personal idiosyncrasies in prior knowledge, however, these pairs were sorted into the three difficulties – easy, medium, and difficult – based on participants' ease of learning judgments (EOLs). During a pretest, participants were given the 45 English words (without the Spanish translation) one at a time. They were asked to say via a slider scale ranging from ‘extremely easy’ to ‘extremely difficult’ (which was scored from 0-1, with 0 being difficult and 1 being easy, which the computer scored to two decimal places) how easy it would be to learn the Spanish translation. The 15 items with the highest EOLs were assigned to the 'easy' condition; the 15 items with the middle judgments were assigned to the medium condition; the 15 items with the lowest EOLs were assigned to be in the difficult condition. There was no difference in EOL judgments among people at different levels of mastery, $F(1,84) = 1.52$, $p = .221$, $\eta_p^2 = 0.02$, perhaps because people took the judgment task to be a 'relative' ease of learning judgment in which they contrasted the items within the set with one another (rather than taking it as an absolute judgment task concerning whether they, personally, could or could not learn the items in question). There was also no difference as a function of mastery in the gamma correlations between their EOLs and their final test performance, $r = -.05$, $t_r(84) = -0.49$, $p = .626$, 95%CI[-0.26, 0.16].

Design. A 3 (Difficulty level – easy, medium, and difficult) x 2 (Experiment Half – first and second half) x 4 (Study Block Duration – 15, 30, 60, 120s), within participant design was used, where Difficulty level was treated as if it were an independent variable. As in the previous experiments, analyses were computed collapsing over the Duration variable. The primary dependent variables of interest were proportion of mind wandering reported in during study (Experiment Half 1 and 2) and proportion correct on the tests.

To examine the impact of mastery on mind wandering during study, performance across tests 1 and 2 was averaged and Z-scores were computed for each participant. These scores were used as the covariate for the ANCOVA analysis. Analyses computed using test 1 and test 2 performance and Z-scores as a metric of mastery were also performed and showed the same pattern of results.

Procedure. The experiment was split into 2 halves. In each half, participants were presented with word pairs to study, and then later tested on their learning. In each Experiment Half, word pairs in each of the easy, medium or difficult blocks, were presented one at a time for 1400ms with a 100ms ISI. Participants were instructed to study them so that later, when they were presented with the English word they could produce the correct Spanish translation. They were queried with a probe, at the end of each block, asking about their attentional state. The attentional probe at the end of each block presented the words "MIND WANDERING" and "ON TASK", as in the previous experiments. The same word pairs were presented in both the first and second Experiment Half, with each pair being presented an average of 19.82 times (SD_{easy} = 3.95; SD_{medium} = 3.82; $SD_{difficult}$ = 3.97) for each participant.

Tests. Participants were asked to provide Spanish translations for the English words presented as cues. All word pairs were tested, with randomized presentation in each test, such that participants were tested twice on each word pair. There was no feedback and participants had up to 10s to respond. Strict scoring was used to determine accuracy.

Results

Test performance. An ANCOVA showed that there was an effect of Difficulty, with proportion correct on the final test being highest for the easy items, then medium difficulty items, and lowest for the difficult items, $F(2,168) = 889.59$, $p < .001$, $\eta_p^2 = 0.91$. There was a main effect of Experiment Half such that participants performed better on Test 2 than Test 1, $F(1,84) = 232.51$, $p < .001$, $\eta_p^2 = 0.74$. There was also a significant Difficulty x Experiment Half interaction, $F(2,168) = 19.60$, $p < .001$, $\eta_p^2 = 0.19$, such that participants improved more on the medium and difficult items from Test 1 to Test 2 than they did on easy items (see Table 1.2). This interaction presumably happened because most of the easy pairs were already well learned by the first test, resulting in a ceiling effect which prevented further improvement for those items. To further examine this interaction, analyses investigating the difference in performance between Test 1 and Test 2 for each level of difficulty was conducted. Participants showed significantly greater improvement for medium-difficulty items, $M = .14$, $SD = .11$, than for easy item, $M = .05$, $SD = .11$, $t(85) = 5.37$, $p <.001$; 95%CI [0.06, 0.13], $d = 0.58$, and they also showed more improvement for medium-difficulty items than for difficult items, $M = .08$, $SD = .09$, $t(85) = 4.55$, $p <.001$; 95%CI [0.04, 0.09], $d = 0.49$. The amount of improvement did not differ between easy and difficult items, $t(85) = 1.65$, $p = .103$; 95%CI [-0.01, 0.06], $d = 0.18$.

		Test Performance	
	EOLs	Test 1	Test 2
Easy	.88 (.10)	.83 (.15)	.88 (.11)
Medium	.47 (.16)	.39 (.19)	.54 (.22)
Difficult	.17 (.11)	.12 (.11)	.20 (.14)

Table 1.2. Ease of learning judgments and performance in Experiment 3

Ease of learning judgments (EOLs) and test performance (proportion correct) for each level of Difficulty in Experiment 3 as proportions with the standard deviations in parentheses.

Most importantly, there was both a Difficulty x Mastery interaction, $F(2,168) = 21.00$, $p < .001$, $\eta_p^2 = 0.20$, and a 3-way Difficulty x Experiment Half x Mastery interaction, $F(2,168) = 11.87$, $p < .001$, $\eta_p^2 = 0.12$. To further examine the 3-way interaction among Difficulty, Experiment, and Mastery, difference scores were computed for each participant by subtracting Test 2 from Test 1 performance, at each difficulty level, and a proportion was then computed by dividing each participant's difference score for each difficulty, by the total change in performance across all 3 levels of Difficulty. Post-hoc correlations between Mastery and the proportion of change in test performance in each condition were then computed (see Figure 1.2). There was a significant negative correlation between Mastery and change in test performance on easy items, $r = -.35$, $t_r(84) = 3.74$, $p < .001$, 95% CI[-0.53, -0.15], such that lower performers showed more improvement from Test 1 to Test 2 on easy items compared to medium or difficult items. Conversely, there was a significant positive correlation between Mastery and proportion of change in performance for difficult items, $r = .31$, $t_r(84) = 2.95$, $p = .004$, 95% CI[0.10, 0.49], such that higher performers improved more on difficult items compared to items of easy or medium difficulty. The correlation between Mastery and proportion change in test performance for items of medium difficulty did not reach significance, although there was a trend in the direction of higher mastery relating to more change in performance, $r = .19$, $t_r(84) = 1.78$, $p = .079$, 95% CI[-0.02, 0.39]. Analyses completed using the raw difference scores of Test 1 and Test 2 performance, showed the same pattern of results, except that the correlation between Mastery and the difference score for medium difficulty was then significantly positively correlated. This pattern of results suggests that the interaction(s) might have resulted, in part, from a ceiling effect on performance for easy materials.

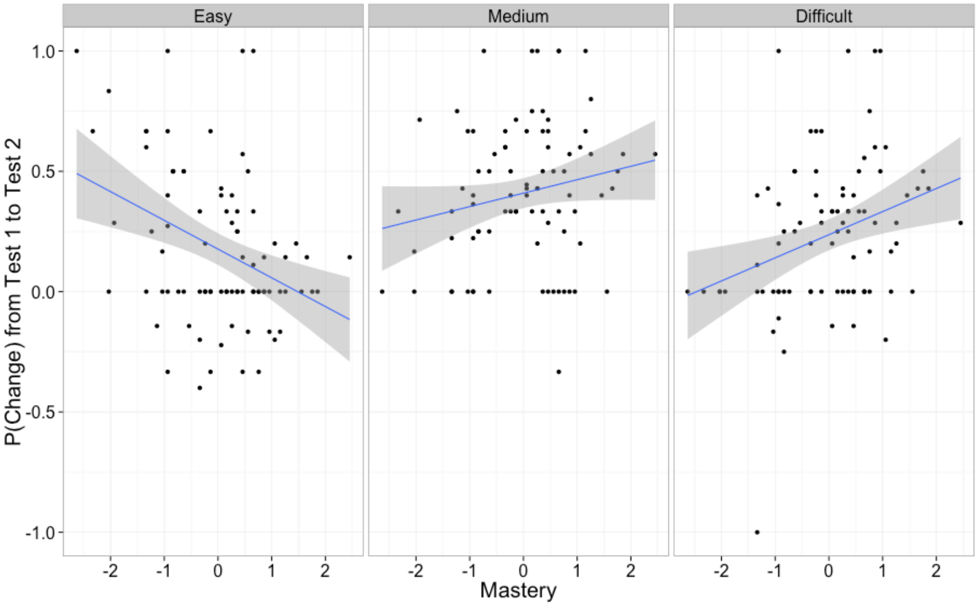

Figure 1.2. Change in performance across mastery in Experiment 3

Change in test performance from Test 1 to Test 2 for each of the 3 levels of Difficulty. All participants are represented in each panel. The line represents the regression line of best fit and the grey shaded area reflects the 95% confidence interval of the regression line. A negative Mastery value reflects that a particular participant did worse on Test 2 than Test 1 for that particular condition. For example, a change of -1 (see bottom left corner of the difficult panel), reflects a case where a particular participants' test performance worsened on those difficult items.

There was no interaction between Experiment Half and Mastery, $F(1,84) = 0.70$, $p = .405$, $\eta_p^2 = 0.01$. The 'effect' of Mastery could not be computed, as Mastery was derived from test performance.

Mind wandering. Overall, the proportion of reported mind wandering was 0.27 ($SD = 0.18$). Two participants did not report any mind wandering. To examine the impact of mastery, difficulty was treated as if it were an independent variable and computed a 3 (Difficulty level) x 2 (Experiment Half) x Mastery ANCOVA on mind wandering. Mastery was computed from averaged and standardized test performance across both test 1 and 2, although the reported statistics hold regardless whether Test 1, Test 2, or averaged Z-scores were used.

There was a main effect of Difficulty on mind wandering, $F(2,168) = 4.53$, $p = .012$, $\eta_p^2 = 0.05$. This main effect is illustrated in the far right panel of Figure 1.1. There was an overall U-shaped pattern in which participants mind wandered less when studying medium difficulty items in comparison with either easy or difficult items. As can be seen from Figure 1.1, this pattern was similar to that shown in Experiments 1 and 2. Post-hoc tests showed that participants mind wandered significantly less when studying medium difficulty items as compared to easy items, $t(85) = 2.63$, $p = .010$; 95%CI [0.02, 0.13], $d = 0.28$, and as compared to difficult items, $t(85) = 3.07$, $p = .003$; 95%CI [0.03, 0.13], $d = 0.33$. There was no difference in the rate of mind wandering between easy and difficult items, $t(85) = 0.23$, $p = .817$; 95%CI [-0.07, 0.08], $d = 0.03$. There was also an expected main effect of Experiment Half, such that participants reported more mind wandering during Experiment Half 2 ($M = 0.35$, $SD = 0.24$), as compared to

Experiment Half 1 ($M = 0.24$, $SD = 0.18$), $F(1,84) = 26.07$, $p < .001$, $\eta_p^2 = 0.24$. Note that the effect of Experiment Half might be associated with item repetition, as the same items were repeated over time. However, it is not possible to distinguish these 2 possibilities given the present data.

The most interesting results of this experiment, however, concern the effects of Mastery. There was a trend toward an effect of Mastery, $F(1,84) = 3.82$, $p = .054$, $\eta_p^2 = 0.04$. , More importantly, for the present purposes, there was a significant Difficulty x Mastery interaction, $F(2,168) = 8.41$, $p < .001$, $\eta_p^2 = 0.09$, as is shown by the ANCOVA results. Participants with higher test scores mind wandered the most on easier items, whereas participants who had lower test scores mind wandered the most on items that were the most difficult. The figure illustrating this interaction is presented in Figure 1.3. There was also a significant 3-way interaction among Difficulty, Experiment Half, and Mastery, $F(2,168) = 4.03$, $p = .02$, $\eta_p^2 = 0.05$.

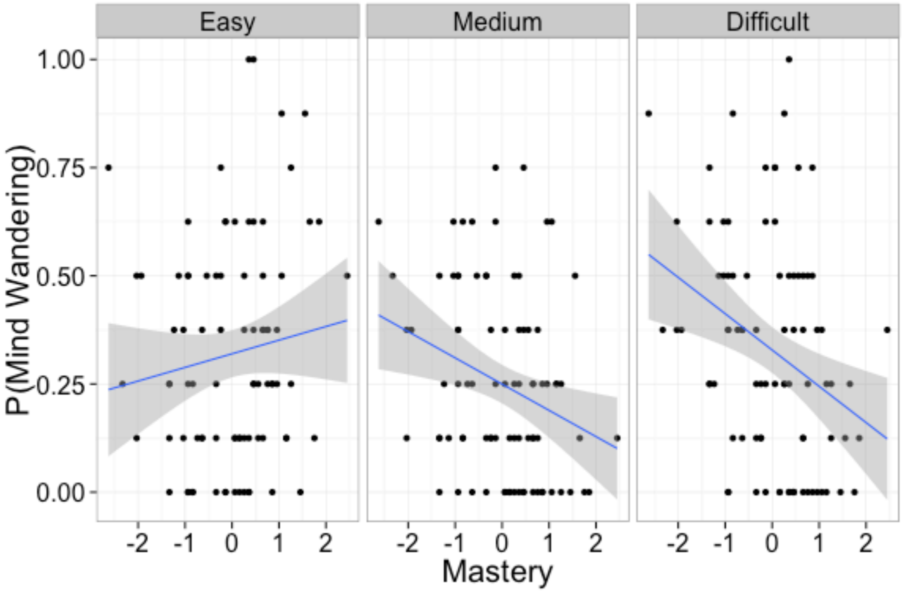

Figure 1.3. Mind wandering across mastery in Experiment 3

Proportion of mind wandering across different Mastery levels separated by Difficulty in Experiment 3. The line represents the regression line of best fit and the grey shaded area represents the 95% confidence interval. Because there were only 8 probes per Difficulty per participant, the proportion is in a factor of 0.125.

There were no interactions between Difficulty and Experiment Half, $F(2,168) = 0.49$, $p = .613$, $\eta_p^2 = 0.01$, or between Experiment Half and Mastery, $F(1,84) = 0.22$, $p = .641$, $\eta_p^2 = 0.003$.

To more clearly illustrate the 3-way interaction of Difficulty, Experiment Half, and Mastery, participants were separated into 3 groups based on standardized test performance and computed the proportion mind wandering for each group across Difficulty and by Experiment Half. Low performers had test scores below $Z = -0.43$; high performers had them above $Z = 0.43$; and middle performers were had scores between $-0.43 < Z < 0.43$. As is shown in Figure 1.4, there was a clear shift in the tendency to mind wander, as a function of mastery, as the items became more difficult. High scoring participants mind wandered on the easy items whereas low scoring participants mind wandered on the difficult items. Interestingly, the pattern shown in the overall data – with mind wandering being highest on both easy and difficult items and lowest when studying the medium-difficulty items was shown only by the middle third of participants: neither the high nor the low performers showed this pattern. The statistics for the breakdown of the data illustrated in Figure 1.4 and as described below.

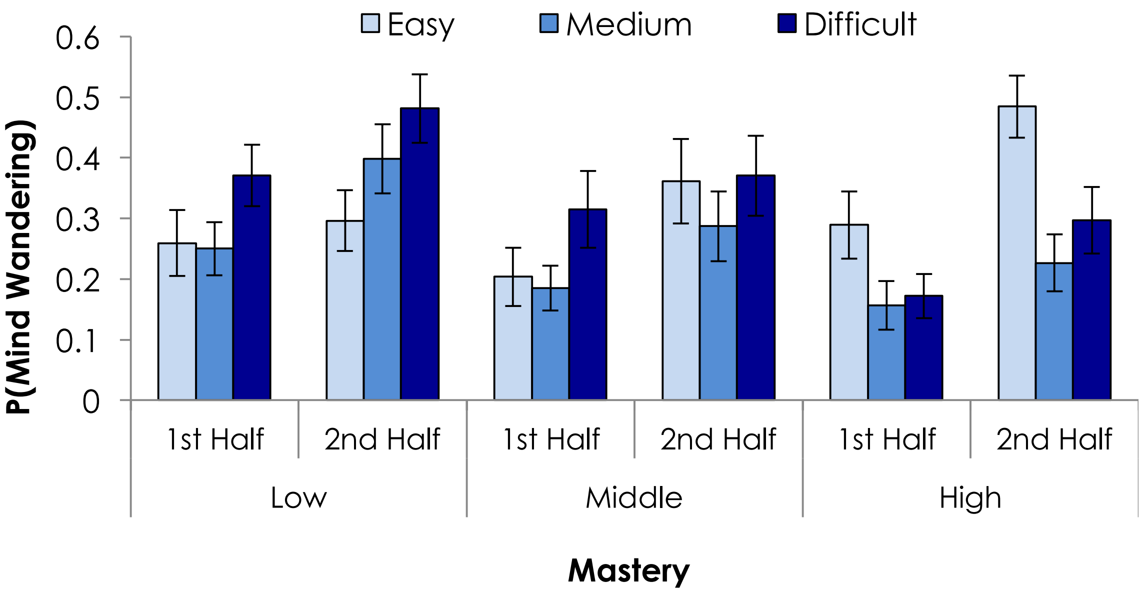

Figure 1.4. Mind wandering across mastery and experiment half in Experiment 3

For illustrative purposes, participants were split into 3 groups based on standardized average test performance. Data from the lowest performers (n = 27, Z < -0.43, test performance from 0.20 – 0.43) are shown in the left panel; the middle panel (n = 27) depicts participants whose average performance was between 0.46 – 0.53; the data from the highest performers (n = 32, Z > 0.43, test performance from 0.54 – 0.77) are shown in the right panel. Error bars reflect standard errors.

The statistics for the breakdown of the data illustrated in Figure 1.4 are derived from a 3 (Difficulty) x 2 (Experiment Half) x 3 (Mastery) ANOVA, in which mastery was treated as if it were an independent variable. The 3 mastery levels – low, middle, and high – were grouped according to Z-scores, such that approximately one-third of participants fell into each group. Low performers had Z-scores below -0.43 (n = 27), high performers had Z-scores above 0.43 (n = 32), and middle performers had Z-scores between -0.43 and 0.43 (n = 27). Similar to results from the ANCOVA, there was a main effect of Difficulty, $F(2,166) = 4.41$, $p = .019$, $\eta_p^2 = 0.05$, and a main effect of Experiment Half, *F*(1,83) = 25.15, $p < .001$, $\eta_p^2 = 0.23$, on mind wandering. There was no effect of Mastery, *F*(2,83) = 1.21, $p = .303$, $\eta_p^2 = 0.03$, suggesting that low ($M = 0.34$, $SD = 0.17$), middle ($M = 0.29$, $SD = 0.20$), and high performers ($M = 0.27$, $SD = 0.17$) did not differ in their overall rate of mind wandering. Figure 1.4 shows mind wandering as a function of Difficulty, Experiment Half, and Mastery. There was only a trend toward a three way interaction in this analysis, however, *F*(4,166) = 2.04, $p = .092$, $\eta_p^2 = 0.05$. The difference between the ANOVA and ANCOVA concerning the significance of this interaction may have been due to a decrease in power when the continuous factor of Mastery was transformed into a nominal variable with 3 levels.

Nevertheless, even with the ANOVA, there was a significant Difficulty x Mastery interaction, *F*(4,166) = 5.31, $p = .001$, $\eta_p^2 = 0.11$. Consequently, post-hoc tests examining the effect of Difficulty were computed at each level of Mastery. The low performers showed a significant effect of Difficulty, *F*(2,52) = 5.52, $p = .007$, $\eta_p^2 = 0.18$, such that they mind wandered more on difficult items than easy items, *t*(26) = 2.94, $p = .007$; 95%CI [0.04, 0.25], $d = 0.57$, or medium-difficulty items, *t*(26) = 2.44, $p = .022$; 95%CI [0.02, 0.19], $d = 0.47$. They showed no difference in mind wandering between easy and medium-difficulty items, *t*(26) = 1.04, $p = .306$; 95%CI [-0.14, 0.04], $d = 0.20$. There was no effect of Difficulty on mind wandering for middle performers, *F*(2,52) = 1.62, $p = .208$, $\eta_p^2 = 0.06$. The high performers showed an effect of Difficulty, *F*(2,62) = 9.15, $p = .001$, $\eta_p^2 = 0.23$, such that they mind wandered more when studying the easy items than when studying the medium-difficulty items, *t*(31) = 4.74, $p < .001$; 95%CI [0.11, 0.30], $d = 0.84$, or when studying the difficult items, *t*(31) = 2.55, $p = .016$; 95%CI [0.03, 0.27], $d = 0.45$. They showed no difference in mind wandering when studying medium compared to difficult items, *t*(31) = 1.07, *p* = .295; 95%CI [-0.13, 0.04], *d* = 0.19.

There were no interactions between Experiment Half and Mastery, *F*(2,83) = 0.20, *p* = .821, η_p^2 = 0.01, or Difficulty and Experiment Half, *F*(2,166) = 0.39, *p* = .677, η_p^2 = 0.01.

Mind wandering and learning across participants. Collapsing data across participants, correlations were computed between mind wandering in each of Experiment Half 1 and 2 and the corresponding test (i.e., mind wandering in Experiment Half 1 with performance on Test 1). There was a negative correlation between mind wandering in Experiment Half 1 and performance in Test 1, *r* = -.25, t_r(84) = -2.33, *p* = .022, 95% CI[-0.44, -0.04]. There was no correlation between mind wandering in Experiment Half 2 and performance on Test 2, *r* = -.16, t_r(84) = -1.52, *p* = .133, 95% CI[-0.36, 0.05]. This might have been because learning occurred in first half of the experiment, such that participants would study materials they had not learned and mind wander on already learned items (which would be correct on Test 2). However, overall mind wandering and final test (i.e., Test 2) performance were negatively correlated, *r* = -.22, t_r(84) = -2.02, *p* = .047, 95% CI[-0.41, -0.001]. Participants who mind wandered more, learned less and performed worse.

Mind wandering and learning within participants. The within-participant effect of mind wandering on learning was not computed, in this experiment, because there had been no pretest so it was not possible to be sure which items were known *a priori*, and which ones were learned during the experiment. Furthermore, because each word pair was presented almost 20 times during this experiment, almost all word pairs would necessarily be binned into both the *on task* and the *mind wandering* category, obscuring any differences.

Combined Analyses of Mind Wandering across Experiments

A comparison across the three experiments was conducted in order to investigate the generality and replicability of these effects of difficulty level on mind wandering. The focus of this analysis was to investigate mind wandering as a function of the three levels of difficulty while ignoring the procedural differences among experiments. The data from all three experiments was used to conduct a 3 (Experiment – between) x 3 (Difficulty – within) mixed model analysis[1]. There was no significant difference in the overall rate of mind wandering across the 3 experiments, $F(2,131) = 2.09$, $p = .128$, $\eta_p^2 = .03$. There was a significant effect of Difficulty on mind wandering, $F(2,262) = 18.20$, $p < .001$, $\eta_p^2 = .12$. Post-hoc tests showed that participants mind wandered more on easy items ($M = .32$, $SD = .25$) than on medium difficulty items ($M = .25$, $SD = .22$), $t(133) = 3.11$, $p = .002$; $d = .27$, 95%CI [0.03, 0.11], and also more on the difficult items ($M = .39$, $SD = .31$) than on the items of medium difficulty, $t(133) = 5.39$, $p < .001$; $d = .47$, 95%CI [0.09, 0.19]. They also mind wandered more on difficult items than on easy items, $t(133) = 2.20$, $p = .029$; $d = .19$, 95%CI [0.01, 0.13]. The main effect of Difficulty was qualified by a significant Experiment x Difficulty interaction, $F(4,262) = 3.16$, $p = .021$, $\eta_p^2 = .05$. Post hoc tests show that there was no effect of Experiment on mind wandering for easy

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[1] Because the variances for difficult items differed among the 3 Experiments, the homogeneity of variance assumption was violated with *Levene's F*-test, $F(2,131) = 8.45$, $p < .001$. Therefore, Welch's ANOVA was computed and Games-Howell was used as the post-hoc procedure to ensure effects were robust. Consequently, some degrees of freedom are estimates with decimal places. For simplicity in describing effects, the label of "medium difficulty" refers RPL items in Experiments 1 and 2, and medium items in Experiment 3.

items, *F*(2,46.58) = 0.05, $p = .955$, $\eta_p^2 = .001$, or for medium-difficulty items, *F*(2,41.78) = 0.11, $p =.894$, $\eta_p^2 = .02$. There was, however, there was a significant effect of Experiment on the difficult items, *F*(2,38.99) = 4.66, $p = .015$, $\eta_p^2 = .08$. Participants mind wandered marginally less on difficult items in Experiment 3 (*M* = .33, *SD* = .26) than in Experiment 1(*M* = .49, *SD* = .31), *t*(29.02) = 2.21, $p = .087$; $d = 0.55$; 95%CI [-0.02, 0.34], and in Experiment 2(*M* = .53, *SD* = .40), *t*(31.95) = 2.43, $p = .054$; $d = 0.60$; 95%CI [-0.003, 0.40]. There was no difference in mind wandering on difficult items between Experiments 1 and 2, *t*(45.82) = 0.39, $p = .696$; $d = 0.11$; 95%CI [-0.29, 0.21]. However, caution should be taken when interpreting these results, as there were several striking methodological differences amongst these experiments, including: (1) RPL was not computed, only assumed in Experiment 3, (2) mind wandering rates were not standardized, and it would be difficult to do so due to these constraints, between experiments, (3) timings for the appearance of the attentional probe differed between experiments and among participants, and (4) the timing and number of word pairs shown differed between Experiments. Overall, though, the results of the three experiments – taken as replications with sometimes rather extreme variations of one another – were strikingly similar.

Discussion

Experiments 1 and 2 showed that studying materials in RPL was associated with reduced levels of mind wandering, while Experiment 3 demonstrated that what qualifies as RPL depends on an individual's mastery of the material. It was also found in Experiment 3, that mind wandering increased over Experiment Half. These data provide evidence that the simple effect of mind wandering based on the difficulty of the materials – the U-shaped pattern of less mind wandering for 'medium' items and more for much easier and too difficult items – can and should be unpacked. The simple effect of Difficulty, in the third experiment – showing the participants mind wandered the least for medium difficulty items – masked the fact that individuals at different levels of knowledge or skill have different RPLs, and show distinctively different patterns of mind wandering. Aggregating the data across all participants made it seem that participants focus on items of moderate difficulty, but this was an illusion. Instead, the pattern was dependent on the extent to which a given participant had already mastered the materials. One size does not fit all, as these data illustrate.

Task Difficulty and Mind Wandering

There are many conflicting findings in the existing literature, some of which suggest that mind wandering increases with task difficulty (Dixon & Bortolussi, 2013; Feng et al., 2013) while others suggest the opposite (Antrobus et al., 1966; Antrobus, Coleman, & Singer, 1967; Filler & Giambra, 1973; Grodsky & Giambra, 1990-91; McKiernan, D'Angelo, Kaufman, & Binder, 2006; McVay & Kane, 2012; Smallwood, Obonsawin, & Reid, 2003; Teasdale et al., 1995, Thomson, Besner, & Smilek, 2013). For example, Feng et al. (2013) and Dixon and Bortolussi (2013) found that mind wandering *increases* when the individual is reading difficult texts. In contrast, data from Antrobus et al., 1966, Filler and Giambra, 1973, McKiernan et al., 2006, Smallwood et al., 2003, Teasdale et al., 1995, and Thomson et al., 2013 all suggest that mind wandering *decreases* as task difficulty and demand increases. These data provide a potential reconciliation for these seemingly contradictory findings.

In the case where mind wandering increased with task difficulty, the RPL account suggests that participants may have had low or no mastery of the tasks. Consequently, the easiest readings (in those experiments) would have been in RPL. As task difficulty increased, the task would have become further removed from the learner's 'sweet spot,' resulting in increased mind wandering. On the other hand, studies showing that mind wandering decreased with task difficulty were most likely on the other end of the spectrum. Those tasks may have been too easy and therefore outside of people's RPL. Increasing the difficulty of those tasks would have brought them into range of RPL and resulted in less mind wandering. Furthermore, the difficulty level of the task that corresponds to RPL depends upon the individual. If a well-read philosopher were to read a children's book, they would most likely mind wander. If they were presented with a more abstruse text, they might well remain focused and on task. In contrast, a layperson might stay engaged when reading a summary of a philosophy essay rather than the abstruse essay itself, but mind wander when presented the exact same material that engages a philosopher's undivided attention. These findings suggest that there is a delicate balance between difficulty and mind wandering, a balance that is reliant both on the difficulty of the task itself, and on the individual's current level of mastery and knowledge. Of course, other factors, such as working memory capacity, the importance of the task, the preferred reward for learning, one's state of fatigue or stress, etc., can also play a role in how often one's mind goes offline. But, even so, using RPL to examine mind wandering affords an opportunity not only to maximize learning gains, but also to simultaneously keep one's mind focused on the task at hand.

These results also suggest that students may sometimes mind wander not because of an inherent lack of motivation, or because of an inability to learn, but rather because the difficulty of the to-be-learned materials is inappropriate. Individuals might want to remain focused when attempting to learn materials more difficult than their RPL, but be unable to remain engaged. Conversely, there is no challenge in studying already mastered information, and the boredom that ensues may lead even highly skilled learners to mind wander. In all, these findings imply that studying materials appropriately titrated to an individual’s current expertise, i.e. those in RPL, can reduce mind wandering, and consequently, enhance learning.

Chapter 2:

Mind wandering and Interleaved Practice

Chapter 2 examines the relation of mind wandering and learning across blocked and interleaved conditions. As discussed in the introduction, one reason why interleaving might be beneficial for learning is because learners are thought to pay more attention in the interleaved than blocked condition (e.g., Greeno, 1970, Hintzman, 1974; Pavlik & Anderson, 2005). If this is indeed the case, then one method to assess these differences might be through mind wandering. Specifically, do people mind wander less when studying materials which are interleaved than those which are blocked?

In recent years, a growing body of work on interleaving and blocking has been focused on the effects on inductive learning (e.g., Birnbaum, Kornell, Bjork, & Bjork, 2013; Carvalho & Goldstone, 2014, 2015; Kornell & Bjork, 2008; Kornell, Castel, Eich & Bjork, 2010; Metcalfe & Xu, 2016; Verkoeijen, & Bouwmeester, 2014; Vlach, Sandhofer, & Kornell, 2008; Wahlheim, Dunlosky, & Jacoby, 2011; Yan et al., 2016; Zulkiply & Burt, 2013). In these experiments, participants were presented with categories of materials in blocked and interleaved conditions, and then tested on their ability to identify new, never-studied exemplars. In line with this growing literature, and as induction has yet to be investigated within the context of mind wandering, the focus of this experiment was to examine the efficacy of interleaved and blocked practice on preventing mind wandering, with inductive learning as the learning outcome.

The paradigm used was adapted from previous work on interleaved and blocked practice (e.g., Kornell et al., 2008; Kornell et al., 2010). Participants were shown a series of images of paintings, drawings or prints of various artists, in either a blocked or interleaved block. In the blocked condition, learners were presented with pairs of artists and paintings belonging to the same artist, whereas in the interleaved condition one were presented with artist-painting pairs scrambled across artists. From time to time, the participants were interrupted by being presented with a mind-wandering probe. When the probe appeared they had to respond by saying whether they were mind wandering or on task. Later, participants were given a test in which they were shown new exemplars of the studied artists' work, and they had to type in the name of the artist. The primary hypothesis, counterarguments notwithstanding, was that people would mind wander more when they were studying in the blocked condition, where all of a single artists' works were presented together, than when they were studying in the interleaved condition, where individual works of different artists were interspersed. Consistent with Chapter 1 Experiment 3, mind wandering should also increase as time on task increased.

Method

Participants. The participants were 66 introductory psychology students at Columbia University and Barnard College who participated for course credit. The mean age was 22.70 (*SD* = 6.93). There were 35 females and 31 males. All procedures were reviewed and approved by the Columbia Internal Review Board for the protection of Human Subjects, and conformed to the strictures of the American Psychological Association.

Materials. The corpus of each of the 24 artists used consisted of 22 prints, drawings, or paintings accessed on the internet, and displayed via a MATLAB program, on the computer screen. All images were scaled to fit within a 700 x 500 pixel rectangle slightly above the middle of the screen on a black background, with the artist's first and last name printed in capital letters in white below the image. Both names were presented because some artists are known by both names, while others tend not to be. For example, Jasper Johns tends to be known by both names whereas Rauschenberg's first name is, perhaps, not consistently used. Although both the first and last name were presented at study, only the last name was asked for at test.

The artists used were: Frida Kahlo, Eva Hesse, Tom Wesselman, Alice Neel, Terry Winters, Sonia Delaunay, Wayne Thiebaud, Richard Serra, Lee Krasner, Sam Francis, Louise Nevelson, Joan Mitchell, Helen Frankenthaler, James Rosenquist, Jasper Johns, Robert Motherwell, Cy Twombly, Robert Rauschenberg, Donald Sultan, Ellsworth Kelly, Francis Bacon, Isabel Bishop, Lucien Freud and Frank Stella.

***Design and procedure*.** The design was a 2 (Condition: blocked or interleaved, within participant) X 2 (Order of condition: blocked first or second, between participants) X 4 (Quartile: first, second, third or fourth, within participant) X 3 (Number of Exemplars, either 12, 15 or 18, within participant).

The works of 12 artists, randomly determined over participants, were assigned to be in the blocked condition and the other 12 artists were assigned to be in the interleaved condition. Either 12, 15 or 18 exemplars were presented for each artist, a within-participants factor that was varied randomly within each quartile. The reason for including Number of Exemplars as a factor, rather than making the number of exemplars presented constant, was to prevent participants from being able to reliably anticipate the mind-wandering probe. Each exemplar was presented for 3 s, with a 1s ISI interval. The mind-wandering probe – which was a screen that asked the participant whether they were mind wandering or on task – appeared after the presentation of the all of the 12, 15 or 18 assigned exemplars of one artist, in the blocked condition (see footnote 2 for the yoked interleaved condition). Thus, in the blocked condition people would see, say, 18 images of Sam Francis' paintings and then a mind-wandering probe. Then they would get, say, 12 images of Frank Stella's paintings then a probe, and then, 15 images of, say, Joan Mitchell's works and then a probe. This would comprise the first quartile of the first half of the experiment. The three levels of the Number of Exemplars was randomly determined within each quartile. After completing study of the first quartile exemplars, participants went straight on to the second quartile, still in the blocked practice condition but with different artists. Then they completed the third and fourth quartiles, until all 12 artists had been studied.[2]

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[2] Participants were yoked such that the yoked person would get exactly the same exemplars as his or her mate, that is, the same 12 artists that his or her partner had in the first half of the experiment –e.g., Sam Francis, Frank Stella, and Joan Mitchell, as well as all of the other 9 artists in the first half, with the exact same exemplars for each. The difference was that in the blocked condition all of the works of a single artist were presented together, whereas for the yoked participant the (12, 15 or 18) works of the 12 artists would be interleaved. The entire deck of 180 works of art studied in the first half of the experiment was the same for the yoked partners, except that in the blocked case the works were organized by artist whereas in the interleaved case they were randomized. The yoked participant got the mind-wandering probes at exactly the same time in the sequence as his or her yoked mate had done. So, if the mind-wandering probes for the blocked partner came after 18 paintings by Sam Francis, 12 by Frank Stella, and 15 by Joan Mitchell, the yoked interleaved partner's mind-wandering probes would come after 18 images, 12 images and 15 images. The yoked partner would also see (the same) 18 Sam Francis works, 12 Frank Stella works, and 15 Joan Mitchell works, but in an interleaved order throughout all 4 Quartiles. During the second half of the experiment, participants enacted the opposite condition, that is, if they had studied in a blocked fashion during the first half of the experiment they studied in a interleaved fashion during the second half of the experiment, but they remained yoked. Different artists were presented in the first and second half of the experiment. For half of the yoked participants, interleaving and blocking were swapped with the

After study and the 12 mind-wandering probes, participants did a short distractor task in which they counted down by 3's from 3078 and then they were tested. The test consisted of the random presentation of 48 new images – 4 per studied artist, in which they were asked to type in the artist's last name. They then went on to the second half of the experiment, which was like the first, but with the alternate interleaved condition and different artists.

At the end of the experiment, participants reported on a 7-point Likert scale: (a) how familiar they were with the artists and paintings, (b) how much they liked the paintings, and (c) how important art was in their daily lives. They also made judgments concerning whether they thought that interleaved or blocked practice was better for learning and on which condition they thought they had mind wandered more.

Results

Learning performance

Answers were computer scored for exact match but each response was also checked by a research assistant to count spelling mistakes as correct. The data reported are those for the human

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above constraints (resulting in 2 pairs of yoked participants), whereas for the other half, the artists that had been presented in the first and second half of the experiment were swapped (resulting in another 2 pairs of yoked participants). The yoking and counterbalanced meant that we completed the full design every 8 participants, resulting in 8 replications over 64 participants. We scheduled several extra participants to ensure against no-shows, and ended up with 66 participants. The 'extra' participants were included in the analyses.

(lenient) scoring, though all of the results reported here also hold for the computer scoring. A 2 (Condition: blocked or interleaved) x 3 (Number of Exemplars) x 2 (Order) ANOVA was computed. The criterion of $p < .05$ was once more used as a threshold for significance.

As shown in Figure 2.1, people performed better in the interleaved condition than in the blocked condition, $F(1,64) = 78.34$, $p < .001$, $\eta_p^2 = .55$, replicating findings by Kornell and Bjork (2008). Ours was a replication with variation in procedural details, and using works of art that were by outstanding known artists and which were highly engaging, while Kornell and Bjork's painting were mostly by unknown artists and were less aesthetically compelling.

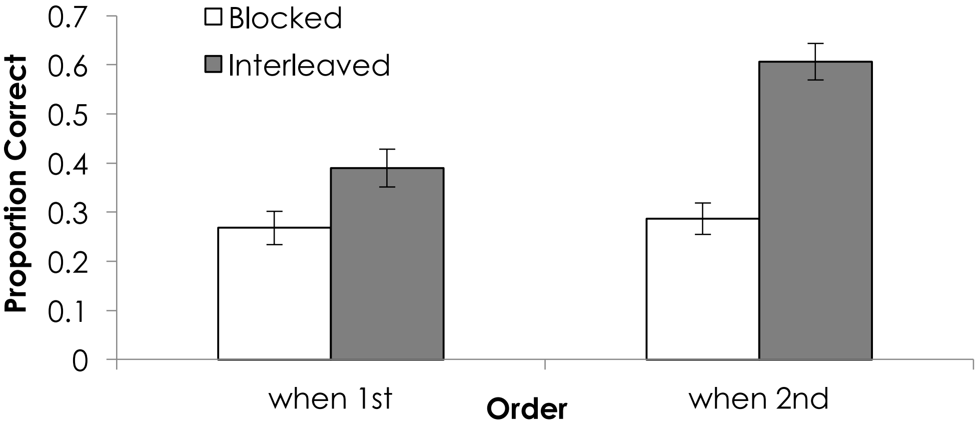

Figure 2.1. Inductive performance across conditions

Leniently scored test performance with standard error bars. Participants who got blocked first (the white bars on the left) are the same people who got the interleaved condition second (the grey bars on the right) and people who got interleaved first got blocked second.

The number of exemplars had a significant (and expected) effect on performance, $F(2,128) = 4.97$, $p = .008$, $\eta_p^2 = .07$, such that mean performance was .34 ($SE = .024$) when they had studied 12 exemplars, .41 ($SE = .027$) when they had studied 15 exemplars, and .41 ($SE =$

.026) when they had studied 18 exemplars. Studying 12 exemplars led to worse performance than studying 15, $t(65) = 2.64$, $p = .01$; 95% CI[0.02, 0.11], $d = 0.32$, or 18 exemplars, $t(65) = 2.62$, $p = .011$; 95% CI[0.01, 0.11], $d = 0.32$. There was no difference in performance between 15 and 18 exemplars, and the number of exemplars did not interact with Condition or with Order.

There was an effect of Order such that participants who studied blocked in the first half of the experiment performed better than those who studied blocked in the second half of the experiment, $F(1,64) = 5.19$, $p = .026$, $\eta_p^2 = .08$. The interaction between Condition and Order was significant, $F(1,64) = 22.28$, $p < .001$, $\eta_p^2 = .26$. As can be seen from Figure 1, performance increased for participants who went from blocked practice in the first half to interleaved practice in the second; it decreased slightly for participants who went from interleaved practice in the first half of the experiment to blocked practice in the second half of the experiment.

Mind wandering

Participants reported mind wandering to .31 (*SE* = .023) of the probes. Crucially, mind wandering occurred more frequently in the blocked condition ($M = .36$, $SE = .028$) than in the interleaved condition ($M = .26$, $SE = .026$), $F(1,64) = 13.75$, $p < .001$, $\eta_p^2 = .18$.

There was an expected effect of ‘time’, such that mind wandering increased with Quartile, $F(3,192) = 24.79$, $p < .001$, $\eta_p^2 = .28$. There was an interaction between Condition and Quartile, $F(3,192) = 5.28$, $p = .002$, $\eta_p^2 = .08$. As is shown in Figure 2.2, there was no difference in mind wandering between the blocked and interleaved conditions during quartiles 1, 2, or 3 (respectively, $t(65) = 0.96$, $p = .34$; 95% CI[-0.04, 0.11], $d = 0.11$; $t(65) = 1.75$, $p = .084$; 95% CI[-0.01, 0.17], $d = 0.22$; $t(65) = 1.18$, $p = .24$; 95% CI[-0.04, 0.15], $d = 0.15$), whereas in quartile 4 there was considerably more mind wandering in the blocked than in the interleaved condition, $t(65) = 4.79$, $p < .001$; 95% CI[0.14, 0.34], $d = 0.60$.

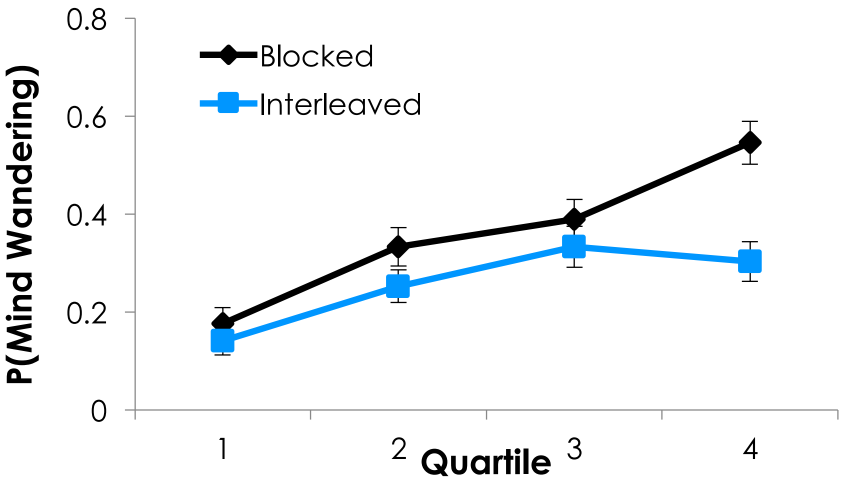

Figure 2.2. Mind wandering over time

Proportion of mind wandering by Quartile. Error bars indicate standard errors of the mean.

Neither the effect of Order, nor the Order by Condition interaction was significant. However, there was a trend toward a three-way interaction among Condition, Quartile and Order, $F(3, 192) = 2.45$, $p = .065$, $\eta_p^2 = .04$. Because it is of some theoretical and practical interest, this nearly significant interaction is shown in Figure 2.3. There are several interesting patterns shown by these data. First, and importantly, the first quartile of the *second* half of the experiment always revealed a reversion to a low level of mind wandering, as compared to the higher mind-wandering level seen in the fourth quartile of the first half of study. This consistent *decrease* in mind wandering from the end of the first half of the experiment to the beginning of the second half of the experiment is consistent with Szpunar, Khan and Schacter's (2014) results showing that interposing a test during the course of study results in a decrease in mind wandering. Here, too, there was release from mind wandering in the middle of the experiment-- probably attributable to the test (but perhaps to the switch in the method of stimulus presentation). These data also suggest that when interleaved practice occurred in the first half of the experiment, followed by blocked practice, the increase in mind wandering in the blocked list over quartiles was especially steep. Indeed, by the end of the blocked condition, when it occurred in the second half of the experiment, the rate of mind wandering was over 60%. When, by contrast, blocked practice was first and interleaved practice occurred in the second half of the experiment, the increase in mind wandering over quartiles in that second half of the experiment was not so great.

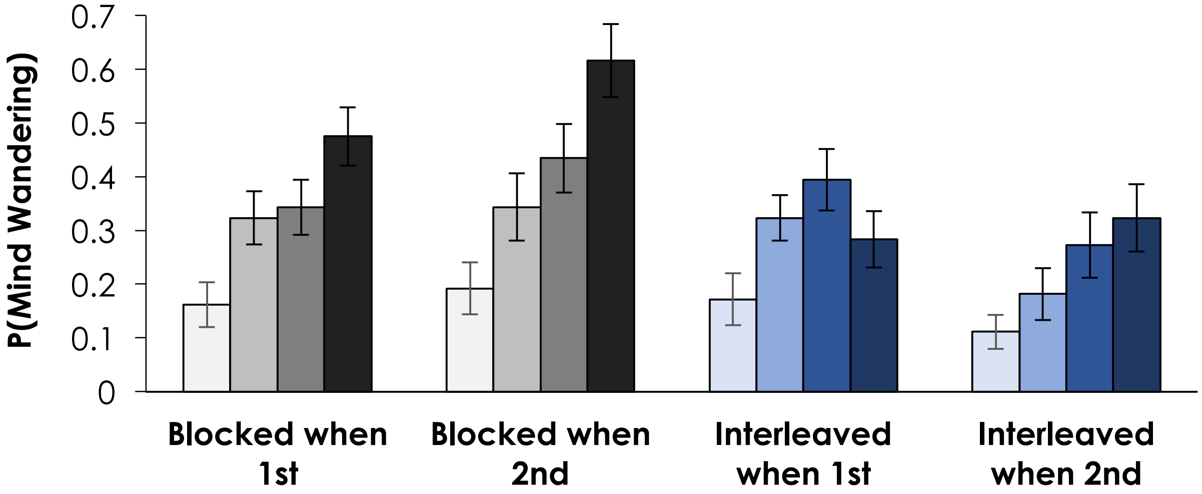

Figure 2.3. Mind wandering over quartile and within each condition

Proportion mind wandering in the blocked and interleaved conditions when blocked practice occurred in the first half or second half of the experiment and when interleaved practice occurred in the first or second half of the experiment. Increasingly dark bars give the proportions of mind wandering, in the first, second, third and fourth quartiles (each consisting of 3 mind wandering probes). Note that individual participants contributed to the Blocked when 1st and Interleaved when 2nd data OR to the Interleaved when 1st and Blocked when 2nd data.

A criticism of this experiment could be that the mind-wandering probes in the blocked condition always came after the last-presented exemplar for one artist, whereas this was not the rule in the interleaved condition. In it, mind-wandering probes sometimes came after the final exemplars of the works of none of the artists, though, towards the end of the list, they could also occur after the presentation of all exemplars of the works of *many* artists. To investigate whether this difference in the frequency of last presented category member in the interval monitored by the mind wandering probe affected the results, the presentation position of the last-of-the-category exemplars in the interleaved condition was determined, and these observations were then binned according to the timing of the 12 mind-wandering probes. This enabled computation of the relative frequency (out of 12) for the last-presented exemplars in each of the 12 probe positions. These participant-specific last-of-the-category exemplars frequencies were then used to *weight* the mind wandering reports that each participant gave at each probe position in both conditions, resulting in two *weighted* mind wandering scores for each participant. Even so, when adjusted, there was still less mind wandering in the interleaved ($M_{interleaved}$ = .32, SE = .05) than the blocked ($M_{blocked}$ = .52, SE = .05) condition, $t(65) = 3.51$, $p = .0008$, d = .43, 95% CI [0.09, 0.31]. Indeed, if anything, the blocked-interleaved difference in mind wandering was larger when the results were adjusted to take the relative frequency of the presence of last exemplars in the interval in the interleaved condition into account.

Mind wandering and performance

Between-participant correlations between mind wandering and performance.

There was a negative correlation between participants' overall level of mind wandering and their later inductive generalization performance, $r = -.35$, $t_r(64) = 3.02$, $p = .004$, 95% CI[-.55, -.12]: participants who mind wandered more learned less. Correlations between the condition-specific performance in the blocked and interleaved conditions with the corresponding proportion of mind wandering in that condition were also computed. There was a negative correlation between proportion of mind and performance on artists studied in the interleaved condition, $r(64) = -.50$, $t_r(64) = 4.64$, $p < .001$, 95%CI [-0.66, -0.30]; but the between-participants correlation between mind wandering and performance in the blocked condition, taken on its own, did not reach significance, $r(64) = -.09$, $t_r(64) = 0.76$, $p = .45$, 95%CI [-0.33, 0.15].

Conditional probabilities of performance as a function of mind wandering. In the blocked condition, it was possible to examine the effect of mind wandering on inductive generalization about *particular* artists, because each attentional probe was linked to a particular artist. The conditional probability of correct induction of the artist to the new paintings at time of test given that the person was mind wandering when studying those artist's exemplars was .21 (*SE* = .028); it was .30 (*SE* = .026) when they had not been mind wandering. These two were significantly different, $t(59) = 3.84$, p < .001, 95% CI [0.04, 0.13], $d = 0.50$, indicating a detrimental effect of mind wandering. Note, some participants reported no mind wandering, as is reflected in the degrees of freedom.

Metacognitive judgements and performance

The majority of participants had fairly accurate metacognitions concerning their performance. When asked in which condition they mind wandered more, 43 participants said the blocked condition, 12 said the interleaved condition, and 11 said there was no difference. When asked in which condition they had learned the artists' names best, 42 said the interleaved condition, 18 said the blocked condition and 6 said no difference. This latter result contrasts with those of Zulkiply and Burt (2013).

Finally, there was a positive correlation between reported art liking and performance, $r(64) = .30$, $t_r(64) = 2.49$, $p = .016$, 95%CI [0.06, 0.50] as might be expected. There was also a correlation between participants' high ratings of the importance of art in their daily life and their performance on the induction task, $r(64) = .27$, $t_r(64) = 2.27$, $p = .027$, 95%CI [0.03, 0.48]. Participants self-reported knowing 1.48 artists on average ($SD = 1.79$). Self-reported artist familiarity was not correlated with performance, nor were any of the self-report measures correlated with mind wandering.

Discussion

It has long been known that stimulus repetition results in habituation, with the attendant loss of attention to the repeated stimulus. Conversely, an orienting response is elicited to novel stimuli, with the attendant increase in attention (see Kahneman, 1973). These attentional principles would seem to have been at work in the present experiment – a plausible explanation of these results, but one that is vague. In response to the call of Smallwood (2013) urging more consideration of possible mechanisms underlying the shift to mind-wandering, it is possible that the mechanism that has been proposed concerning when and why people stop studying one item and switch attention to another might bear on when people will stop studying and switch to mind wandering.

Several of the models of study time allocation proposed in the learning literature include stop rules concerning when the person will cease to study the item at hand. The two most prominent rules are (1) the 'learned to criterion' rule of the Discrepancy Reduction model (Dunlosky & Thiede, 1998), and (2) the 'not learning fast enough' rule in the Region of Proximal Learning model (Metcalfe & Kornell, 2005). The former says that people stop studying when they have reached an internal criterion indicating that the item is sufficiently learned. The latter says that people stop when the derivative of the perceived information uptake function approaches a small subjectively-determined value, that is, when people perceive that they are no longer taking in new information. This can happen because they have learned the material or because it is too difficult to afford learning. But regardless of which rule one champions, both apply on a moment by moment basis, and both would result in more stopping in the blocked than the interleaved condition. Given that the immediately preceding items, in the blocked condition, are highly informationally redundant with the current item, that redundant information contributes to nearness to the learning criterion and to the feeling of not currently uptaking much new information. Both models, then, predict that the stop rule conditions will be more satisfied in the blocked than interleaved condition. One possibility is that when the conditions of the stop rule are met, in the current situation, rather than switching to a different external stimulus, people might switch to internal thought, i.e., they might start mind wandering. But once they switch to mind wandering they are no longer engaging in any processing of the to-be-learned items. With no processing, learning of the externally presented materials presumably ceases. Mind wandering itself, then, results in reduced learning, as many researchers (e.g., Risko, Anderson, Sarwal, Endelhardt, & Kingstone, 2012; Smallwood, Fishman, & Schooler, 2007) have shown. This would result in a negative feedback loop: lack of perceived learning of the to-be-remembered items results in stopping studying, which results in mind wandering, which results in lack of learning of the additional to-be-remembered items. Because the stop rule is more likely to be satisfied in the blocked condition, this feedback loop occurs more in that condition.

This experiment replicated the finding that interleaved practice results in better inductive learning than blocked practice. It also showed that people mind wandered more in the blocked than in the interleaved practice condition. These findings point to a complex attentional contribution to the difference in inductive learning that is observed as a result of blocked versus interleaved practice, whereby the perceived lack of learning in the blocked condition may itself be a trigger to mind wander, but once engaged in mind wandering further learning of the task at hand is likely to be precluded.

Chapter 3:

Neurocognitive Effects of Mind Wandering

Although Chapters 1 and 2 identified conditions under which one is less likely to mind wander, and showed the negative impact mind wandering has on learning, what are the neurocognitive mechanism resulting in this learning decline? Understanding the neural differences when a person is in a mind wandering state supposedly 'learning' is an important question, and one that this chapter attempts to address using event-related potentials or ERPs.

It is known from previous ERP work that early sensory and attentional processing is diminished when mind wandering (e.g., Braboszcz & Delorme, 2011; Broadway et al., 2015; Kam, Dao, Farley, Fitzpatrick, Smallwood, Schooler, & Handy, 2011; Kam, Dao, Stanciulescu, Tildesley, & Handy, 2013; O'Connell, Docktree, Robertson, Bellgrove, Foxe, & Kelly, 2009). While these findings might be a part of the puzzle in explaining the learning decrements occuring during mind wandering, the impact of mind wandering on learning-related processing has not yet been thoroughly examined.

Electrophysiological work on deep processing during learning has demonstrated that the neural signature at time of encoding is different for items that are subsequently remembered or not remembered. Paller, Kutas, and Mayes (1987) found that when ERPs at study were categorized on the basis of subsequent test performance, items that were subsequently remembered elicited larger ERPs from 400-800 ms than those that were forgotten. Jacoby's (1991) process dissociation model posits that retrieval from memory – which presumably depends on initially deep conscious processing – is required to recollect materials, as is thought to be important for recall. Mere fluency or familiarity with the materials – presumably only requiring shallower processing – may be sufficient for recognition (e.g., Jacoby, 1991; Jacoby, Toth, & Yonelinas, 1993). Indeed, an ERP experiment showed that the late positivity ERP difference between recalled and unrecalled materials was larger than the difference between recognized and unrecognized materials (Paller et al., 1988). Because recall is more strategic than recognition requiring greater recollection-based processing, these differences suggest that the encoding-related ERPs might indicate the degree of deep or elaborative processing engaged in during encoding. The ERP differences associated with subsequent recall have generally occurred, as noted in the introduction, relatively late, from 400-800 ms (Paller et al., 1987), with little difference in earlier sensory processing, as indexed by components such as the P1. Thus, if mind wandering reduces task-relevant encoding, it follows then, regardless of what else happens during mind wandering, that the amplitude of this sustained late ERP component, might be diminished during off-task thought.

In the experiment reported here, participants studied English-Spanish word pairs while intermittently being probed for whether they were 'on task' or 'mind wandering.' At the end of stimulus presentation, they completed a cued-recall memory test designed to assess their learning. ERPs during study were compared depending on whether participants had reported being on task or mind wandering during presentation. If participants failed to process the task-relevant information deeply when mind wandering, then the magnitude of the late positivity to stimuli presented while the person was mind wandering should be attenuated relative to those observed when participants reported that they had been on task.

Method

Participants. A total of 31 participants were recruited from the Columbia University community and were compensated at a rate of $15/h for their time. All participants were native English speakers with no self-reported history of any psychiatric disorder. Two participants were excluded – one for sneezing continually and therefore engendering too much noise in their EEG recording, and one for improperly performing the task (i.e., for rotely retyping the English cue word in both the pretest and final test) – resulting in 29 usable participants (15 males and 14 females; *M* = 24.03 years old, *SD* = 4.46). All participants gave written, informed consent and were treated in accordance with the ethical principles of the APA, and the Internal Review Boards of Columbia University and the New York State Psychiatric Institute.

One participant, whose data were included in the ERP tracings below, did not complete the final test. All analyses were, however, also computed with this participant removed and there were no differences in the pattern of results.

Materials. The materials were 179 English-Spanish word pairs taken from Chapter 1, with 35 pairs sorted into each of the easy, medium difficulty and difficult conditions.

Word pairs were presented for study using a 3 (Difficulty of word pairs: easy, medium and difficult) x 4 (Time during which pairs at the same level of difficulty were presented, 15, 30, 60 or 90 s prior to the presentation of an attentional probe) x 2 (study presentation Half) within-participants design. Successive pairs at a single level of difficulty were presented for study at a rate of 1.5 s per pair, until the designated amount of time (15, 30, 60, or 90s) had passed, in what will be called a block. At the end of each so-constructed block, a mind-wandering probe was presented. 12 blocks in the 3 X 4 design, were presented in each study presentation Half. The order of presentation of the 12 blocks in each of the two halves, was randomized with the following constraints: (1) Difficulty was randomized and permuted a total of 4 times, (2) all three difficulty levels were presented at each of the 4 time conditions, in a randomly assigned order, and (3) the position in the sequence of blocks of each difficulty level was equated across participants.

Word pairs were presented in blocks at the 3 levels of difficulty, because past research indicated that experts tend to mind wander on easy materials whereas novices tend to mind wander on more difficult materials (Xu & Metcalfe, 2016). Blocking ensured that participants would get streams of items together at roughly the same level of difficulty. The blocked presentation of materials across particular levels of difficulty was done to ensure that all participants – whether experts or novices – would mind wander on at least some of the materials. The number of seconds for which materials at a particular difficulty level were presented was varied to prevent participants from anticipating the appearance of each mind wandering probe. Additionally, of course, people tend to mind wander more the longer it has been since the last mind wandering probe. Finally, a short break in the middle of the study phase – segmenting the study stream into first and second halves – was added to enable the checking of, and correcting when necessary, of electrode impedances.

There were 25 pairs in each of the three difficulty level conditions. Each pair was presented repeatedly over the course of study, within its own difficulty level blocks, but repeated randomly in all of the Time conditions. Each word pair ended up being presented an average of 10.17 times (*SD* = 3.03) during study.

The dependent variables were cued recall, which was assessed at the end of the experiment, mind wandering, which was assessed at the end of each block, and ERP voltage, which was assessed throughout the study phase, time locked to the onset of each to-be-learned pair.

Procedure. The experiment consisted of 3 sections: pretest, study, and final test. ERPs were recorded during the study phase. During the pretest, participants viewed the English words and were given up to 10s to provide the correct Spanish translation. In the event that they did not know the answer, participants were instructed to try and provide an educated guess of what they thought the translation might be. After each response, participants were asked to provide a judgment of learning (JOL) on a slider scale for word pairs they had answered incorrectly. This allowed pairs to be sorted into three difficulty levels based on strictly-scored pretest accuracy and JOLs – *easy* items were correctly recalled on the pretest; *medium* items were inaccurate on the pretest but were accompanied by high JOLs; *difficult* items were inaccurate on the pretest and accompanied by low JOLs. Thirty-five items were sorted into each condition: 25 of which were presented for study, and 10 of which were reserved to be unstudied control items which were given on the final memory test.[3]

After completing the pretest, participants were presented with the English-Spanish word pairs and asked to study them for an upcoming test. Participants were also told that, intermittently, they would be asked to report whether their attentional state was either ‘on task’ or ‘mind wandering,’ by pressing one of two keys. All participants received and were asked to repeat the definitions of ‘on task’ or ‘mind wandering’ prior to the study phase to ensure they understood what the terms meant. Participants went through the 24 study blocks, with each of the word pairs presented on screen for 1000 ms followed by a blank screen for 500 ms with mind wandering probes interspersed during presentation at the end of each block, as indicated above. The English word was 100 pixels above the midpoint of the screen and the Spanish word was 100 pixels below the midpoint.

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[3] One participant provided only 25 correct responses. For this participant, all of the 25 ‘easy’ word pairs were presented for study, and the participant did not have any unstudied easy control items.

After completing the study phase, participants were given a cued-recall test. Each English word was presented onscreen and participants were asked to type in the correct Spanish translation. All word pairs presented for study were tested, as were the additional unstudied 10 word-pair controls. Presentation order was randomized and no feedback was provided. Participants' responses were leniently scored offline by a research assistant for accuracy.

EEG recording. Brain electrical activity was recorded during the study phase from 62 scalp sites (sintered Ag/AgCl) mounted in an Electrocap (Neuromedical Supplies) and digitized at 500 Hz (DC; high-frequency cut-off of 100-Hz; right-forehead ground). Electrodes were placed on the outer canthus of each eye to record horizontal eye movements, and directly above and below the left eye for vertical movements. Activity was originally referenced to the nose and re-referenced offline to the average of the left and right mastoids. Impedances were maintained below 10kΩ throughout the experiment.

Data Analyses. ERPs were time-locked to word pair presentation and computed with a 200 ms baseline. Since the question of interest was the impact of mind wandering on learning, only the 7 items presented during the 12 s immediately preceding each attentional probe were used in the ERP mind-wandering or on-task averages. This follows the procedure used by previous researchers (e.g., Smallwood et al. 2008; Kam et al., 2011; Kam et al., 2014). ERPs for the 7 items preceding each probe were collapsed and were also averaged across Difficulty, and Time conditions for each of the two Halves of the experiment. They were categorized based on participants' reported attentional state for each block (i.e., on task or mind wandering). ERPs were computed using EEGLAB (Delorme & Makeig, 2004) and ERPLAB (Lopez-Calderon & Luck, 2014).

Prior to analyses, all recordings were filtered using a 0.1-10Hz IIR-Butterworth bandpass filter to remove DC drift and muscle movements. Offline artifact rejection and independent component analysis (Makeig, Debener, Onton, & Delorme, 2004; Makeig & Onton, 2011; ADJUST toolbox: Mognon, Jovicich, Bruzzone, & Buiatti, 2011) were used to remove eye blinks, eye movements, and other muscle activity. For two participants, 1 electrode had to be interpolated due to an abnormal EEG pattern (P1 and CZ, respectively).

Results

The criterion for significance was set at $p < .05$ for all analyses. Partial eta squared (η_p^2) was used as the measure of effect size for ANOVA. *F*-tests with Greenhouse-Geisser adjusted degrees of freedom were used when the assumption of homogeneity of variance was violated. When applicable, post hoc Tukey tests were computed for follow-up comparisons and are directly reported.

Behavioral Data

Final Test Performance. Test performance was computed based on the proportion of leniently-scored items participants answered correctly, and are reported in Table 3.1. Average performance on the final cued-recall test was .58 (*SD* = .09). There was an expected main effect of Difficulty on test performance, $F(1.45, 39.08) = 368.40$, $p < .0001$, $\eta_p^2 = 0.93$, such that participants performed best on easy, next best on the medium, and worst on difficult pairs. Final test performance on easy pairs was significantly better than on medium or difficult pairs, $t(54) = 8.56$, $p < .0001$, and, $t(54) = 26.58$, $p < .0001$, respectively. Performance on medium pairs was higher than on difficult pairs, $t(54) = 18.03$, $p < .0001$. Learning scores computed from the difference between studied and unstudied pairs that had been wrong on the pretest (i.e., the medium and difficult pairs) indicated that participants learned more medium ($M_{difference}$ = .25, SD = .16) than difficult pairs ($M_{difference}$ = .15, SD = .12), $t(27) = 2.23$, $p = .034$, $d = .66$.

Analyses by the Time condition could not be performed as the to-be-learned pairs were repeated randomly many times over all of the Time conditions.

		Difficulty		
		Easy	***Medium***	***Difficult***
Mind Wandering		.40 (.26)	.34 (.23)	.33 (.29)
Final Test Performance	*Studied*	.95 (.07)	.75 (.19)	.17 (.14)
	Unstudied	.91[1] (.15)	.51 (.21)	.01 (.04)
	Overall[2]	.95 (.05)	.68 (.18)	.12 (.11)

Table 3.1. Behavioral results (mind wandering and test performance) in Chapter 3.

Proportion of mind wandering and leniently-scored test performance across Difficulty with standard deviations presented in parentheses. [1]One participant did not have any unstudied easy items given their pretest performance. [2]Overall performance is a weighted mean of the 25 word pairs which were studied and the 10 which were unstudied.

Mind wandering. Participants reported mind wandering an average of .36 (SD = .20) of the time. Collapsing over the Time condition. A 3 (Difficulty) x 2 (Study Half) ANOVA revealed that the rates of mind wandering were fairly consistent across easy, medium, and difficult pairs, $F(1.96, 54.87) = 0.88$, $p = .418$, $\eta_p^2 = 0.03$ (see Table 3.1 for means). There was an expected effect of Study half, such that participants mind wandered more in the second half

(*M* = .41, *SD* = .25) than in the first half (*M* = .30, *SD* = .20), *F*(1, 28) = 8.18, *p* = .008, η_p^2 = 0.23. There was no interaction between Difficulty and Study Half, *F*(1.90, 53.17) = 2.32, *p* = .111, η_p^2 = 0.08.

A 4 (Time) x 2 (Study Half) analysis, collapsing over Difficulty, was also computed. As anticipated, the same reliable effect of Study Half, showed up in this analysis as in the previous one. There was also a main effect of Time such that, as expected, participants mind wandered more on longer relative to shorter blocks, *F*(2.75, 76.88) = 4.18, *p* = .010, η_p^2 = 0.13. There was more mind wandering reported for the 90s as compared to 15s block, *t*(84) = 3.09, *p* = .014. Participants also trended to mind wander more on the 60s as compared to the 15s block, *t*(84) = 2.52, *p* = .064. There was no difference in the rate of the mind wandering between blocks lasting 15 and 30s [*t*(84) = 0.80, *p* = .853], 30 and 60s [*t*(84) = 1.71, *p* = .321], 30 and 90s [*t*(84) = 2.29, *p* = .109], or 60 and 90s [*t*(84) = 0.57, *p* = .940]. There was no interaction between Time and Study Half, *F*(2.57, 71.89) = 0.52, *p* = .640, η_p^2 = 0.64.

Mind wandering and Performance. The between-participant correlation between mind wandering and final test performance was not reliable, *r* = -.30, *t*(26) = 1.60, *p* = .121.

ERP Data

Omnibus ANOVAs were conducted using Electrode (as described below) as an independent variable and treating Attentional State (on task vs. mind wandering) as if it were an independent variable. Average amplitude was computed over the measurement time windows of interest as described below.

ERP waveforms, presented in Figure 3.1, were time locked to the presentation of a word pair during study and categorized according to self-reported attentional state (mind wandering/on task). Only ERPs to word pairs presented 12s, or 7 word pairs, before each probe were included, following Kam et al., 2012, Kam et al., 2014, and Smallwood et al., 2008. Across participants, 63.47% of trials were on-task trials (*SD* = 19.75%) and 36.53% were mind wandering trials (*SD* = 18.66%).

Although the primary hypothesis was in the late positivity, three standard ERP components were investigated. First, analyses were performed on the early P1 component from 70-120 ms, peaking at around 95 ms post-stimulus. This component has been investigated in previous mind-wandering experiments and is usually thought to reflect basic visual-sensory processing. Second, was a P2 component around 170 ms to 250 ms, peaking around 225 ms post-stimulus. This component has not been investigated before in the context of mind wandering, and is sometimes thought to indicate attention-modulated perceptual processing (e.g., Luck & Hillyard, 1994, Crowley & Colrain, 2004), and possibly related to early or short-term encoding (e.g., Dunn, Dunn, Languis, & Andrews, 1998; Chapman, McCrary, & Chapman, 1978). Third, and most importantly, analyses were computed on a late, sustained positive slow wave beginning at around 250 ms and lasting until 800 ms. This component has not previously been investigated in the context of mind wandering.

In line with previous research, analyses of the P1 component focused on the PO3, PO4, and Oz electrodes, as these electrodes overlie occipital cortex (see Kam et al., 2011). A subset of parietal electrodes – PZ, P1, P2, P3, P4, P5, and P6– were chosen based on scalp topography for analyses of both the P2 component and sustained positive slow wave. ERPs were collapsed across attentional state to compute the grand average topography (data not shown), and the electrode sites used for analyses were selected were the subset of electrodes maximally active during 170-250 ms and 250-800. Figure 3.1 illustrates the on-task and mind-wandering ERPs (and difference waves) at electrodes PZ, P1, and P2.

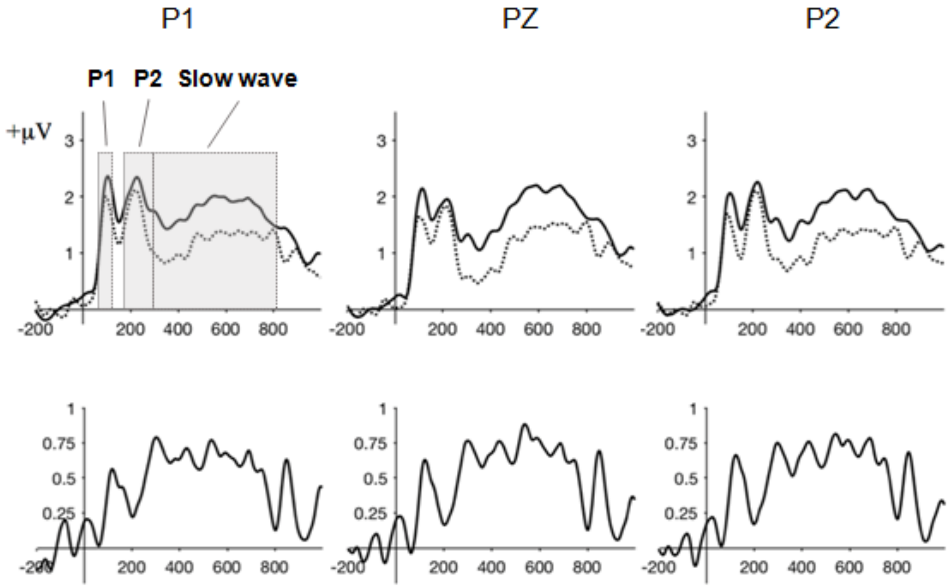

Figure 3.1. Event-related potentials during mind wandering

ERPs to Word Pairs presented during study for electrodes PZ, P1, and P2. *Top Panel.* On-task trials are represented by the solid black line and mind-wandering trials are dotted. Components and time windows analyzed are shaded and labeled in the leftmost panel for the P1 electrode. *Bottom Panel.* Difference waveforms with the mind wandering ERPs subtracted from the on-task ERPs.

Note that the P1 component was analyzed at electrodes PO3, PO4, and OZ (not shown).

The difference between on-task and mind-wandering conditions on the P1 component showed only a marginal effect, $F(1,27) = 3.20$, $p = .085$, $\eta_p^2 = 0.11$, which was in the expected direction of higher amplitude for on-task than for mind-wandering pairs. Although this effect was not quite significant by a two-tailed test, the direction was consistent with past research which has shown effects of mind wandering on sensory processing as reflected by the P1 component (e.g., Kam et al., 2011; Broadway et al., 2016).

There was also a significant difference between on-task and mind-wandering from 170-250 ms – the P2 component. The ERP amplitude was attenuated when participants were mind-wandering relative to when they were on-task, $F(1,27) = 4.19$, $p = .050$, $\eta_p^2 = 0.13$. From past research, it might be reasonable to assume there might be an attenuation in perceptual processing when mind wandering (which has not been previously investigated). Indeed, this difference was found in these data, as indexed by this P2 attenuation during mind wandering.

Finally, and most importantly, there was an effect of mind wandering from 250-800 ms, $F(1,27) = 5.48$, $p = .027$, $\eta_p^2 = 0.17$, such that mind wandering significantly attenuated processing relative to the on-task state during this time window. This pattern of late attenuation during mind wandering has not been investigated before, and suggests that higher-order, deep semantic processing of to-be-learned materials was dampened.

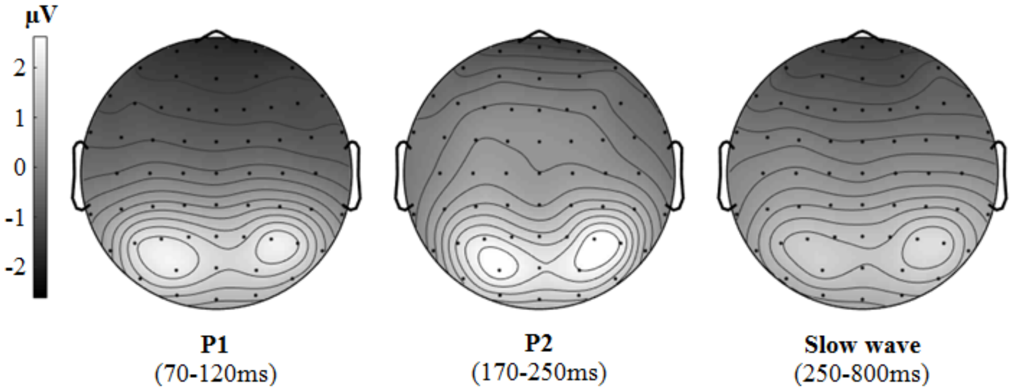

Figure 3.2. Differences in scalp topography

Scalp Topography of the Difference waveforms (mind-wandering ERPs subtracted from on-task ERPs) for the P1, P2, and Slow wave components.

Discussion

This experiment examined the question of whether mind wandering attenuates deep processing as reflected in a late, sustained positive-going process. The prediction was that this processing would be reduced when participants were mind wandering relative to when they were on-task. And, indeed, a significantly attenuated brain response was associated with mind wandering. The data presented here indicate that processing of materials is attenuated by mind wandering at all levels of processing – at the sensory level (the P1), at the perceptual level (P2) and at the deep semantic processing level associated with durable encoding. Given these findings, several key questions and issues arise.

As noted in the introduction, there is considerable research on the Dm effect indicating that ERPs during study of items that are later remembered are larger and more positive – particularly after about 400 ms – than are those of items that are subsequently forgotten at test (e.g., Paller et al., 1988; Paller et al., 1987). Although there were some suggestions that that the Dm effect might be localized to frontal and posterior scalp areas, thought to reflect two distinct memorial processes (e.g., Johnson, 1995), investigations have shown that the Dm effect can vary according to a number of factors. For example, semantic processing has been shown to modulate the onset latency (Neville, Kutas, Chesney, & Schmidt, 1986) and magnitude of the Dm effect (Neville et al., 1986; Van Petten & Senkfor, 1996). Specifically, the Dm effect for semantically-unrelated stimuli was smaller and the onset was later than the Dm effect for semantically-related stimuli (the latter assessed by asking participants whether the final word in the sentence 'fit' the preceding context in Neville et al., 1986; and when participants made positive rather than negative semantic judgments in Van Petten & Senkfor, 1996).

To examine whether or not the effect of mind wandering on late processing was similar to the Dm effect, the ERP data in the present experiment was reanalyzed based on whether the pairs were subsequently remembered or forgotten at test. The Dm effect at the PZ electrode in these data is plotted adjacent to the on-task/mind-wandering ERPs in Appendix 1. Unlike the mind wandering versus on-task contrast, there was no Dm effect at the early P1 and P2 component time windows, $F(1,27) = 1.25$, $p = .274$, $\eta_p^2 = 0.04$, and $F(1,27) = 1.76$, $p = .196$, $\eta_p^2 = 0.06$, respectively. However, as was found in the mind-wandering versus on-task contrast, processing was greatly attenuated from 250 ms to 800 ms for items subsequently forgotten relative to those that were subsequently remembered, $F(1,27) = 14.04$, $p < .001$, $\eta_p^2 = 0.34$. A visual comparison between the left (on task and mind wandering ERPs) and right (Dm effect) panels suggests that, as well as dampening sensory and attentional processing, mind wandering may result in an attenuation of just the type of deep processing required to encode information into memory. These results suggest that the enhancement in late processing, presumably reflected by the larger positive-going activity during on-task performance is qualitatively similar to the Dm effect.

What about the relation of mind wandering and learning? While the between-subject correlation of mind wandering and learning correlation was negative, it was nonsignificant. Importantly, though, there were insufficient participants to appropriately compute a reliable estimate. At least 28 subjects are required for a strong correlation and 85 would be needed for a moderate correlation (Cohen, 1992). The more appropriate analysis would be a within-subject comparison. Unfortunately, because the word pairs repeated many times over the course of the study phase, it is impossible to directly evaluate the impact of mind wandering on learning of particular word pairs. Insofar as each word pair was seen more than 10 times during study, there were instances in which a participant would have reported mind wandering, being on-task, and also cases in which their attentional state was unknown (e.g., at the beginning of a block, rather than one of the 7 pairs which were designated as on-task or mind-wandering) during the presentation of each pair. This feature of the design makes it difficult to clearly segment items into those that had been presented while the participant was mind wandering and those that had been presented when he or she was on task. As such, while learning might be hindered when one is mind wandering, the design of this experiment precludes proper analysis to test this relation.

To the extent that the Dm effect and the late mind-wandering effect reflect similar mechanisms, these results suggest that the late processing observed may be qualitatively similar to the subsequent memory effect, and may be disrupted during mind wandering. Future experiments should assess whether this is, indeed, the case. To conclude: the findings of this experiment indicate that when a person is mind wandering, deep processing, which is associated with higher-order cognitive functions such as semantic encoding, is impaired.

Chapter 4:

Mind wandering, ERPs, and Interleaved Practice

The aims of the experiment to be presented were twofold. The first goal was to thoroughly examine the role of attention in interleaved and blocked practice. While the benefit of interleaving on improving learning and decreasing mind wandering in Chapter 2 supports an attentional explanation (e.g., Greeno, 1970), and suggests that there was increased encoding strength in the interleaved condition, no direct comparisons of encoding strength at study were made. One way to assess this difference might be the extent to which the learner is engaged and processing the information. The late positivity found in Chapter 3, which was attenuated during episodes of mind wandering and thought to be associated with encoding-related processing, could be one such marker of encoding strength during study. Therefore, if interleaving recruits more encoding strength, ERP amplitudes should be greater in the interleaved relative to blocked condition.

The second goal of this experiment was to extend the findings from Chapter 3. While the difference in late processing between on-task and mind wandering found in the previous chapter was qualitatively similar to the Dm effect, the design of the experiment made it difficult to examine the effect of mind wandering on learning. As such, an additional investigation into the relation of mind wandering and deep processing in a learning context was warranted.

The procedure was adapted from Chapter 2. Participants were first asked to study painting-artist pairs in either the blocked or interleaved condition, and then tested on their learning. Participants were then asked to study the remaining paining-artist pairs in the other condition, and were tested on their learning once more. Participants were intermittently interrupted during study and asked to report whether they were mind wandering or on-task. ERPs were recorded during the study phase in order to identify processing differences at study that might result in these previously observed learning differences between blocked versus interleaved conditions. The tests comprised of an old/new item recognition test, followed by a category recognition test, wherein participants were shown an exemplar and asked to identify whether it was old or new. An artist name was then shown below the exemplar, and participants were asked to identify whether the artist name displayed was the correct name or not.

The prediction was, again, that participants would mind wander more in the blocked condition, and inductive performance would be better for interleaved categories. In addition, as mind wandering is thought to reduce deep semantic encoding, but not shallow encoding (Thomson et al., 2014), participants' old/new item recognition performance should not differ between on task and mind wandering states. Instead, participants' ability to recognize the artists which they mind wandered on when studying should be diminished. Finally, if the deep processing found in Chapter 3 when a person reports being 'on task' is associated with encoding, this should also be the type of processing that is heightened in the interleaved condition.

Method

The overall method, namely the procedure, counterbalancing, ordering, and design of the study halves, was identical to Chapter 2. Screening of participants, ethics compliance, and EEG-related procedures were identical to Chapter 3. Any and all changes are described below.

Participants. A total of 41 individuals completed the experiment and were compensated \$30 of their time. One participant was excluded because they reported feeling unwell since they had not eaten breakfast, and it was unclear how it might have affected their behavior or brain waves. This left 40 usable participants (22 females, $M = 23.53$ years, $SD = 4.11$).

Materials. A total of 22 paintings each, for 24 different artists was obtained online. Many of these were from Chapter 2, but several artists were replaced (e.g., Frida Kahlo), since a large proportion of participants had previously reported knowing them. The artists used were: Alive Neel, Cy Twombley, David Milne, Donald Sultan, Ellsworth Kelly, Emily Carr, Frank Stella, Helen Frankenthaler, Isabel Bishop, James Rosenquist, Jasper Johns, Jean Dubuffet, Jean-Michel Basquiat, Joan Mitchell, Kazimir Malevich, Lee Krasner, Richard Serra, Robert Motherwell, Robert Rauschenberg, Sam Francis, Sonia Delaunay, Terry Winters, Tom Wesselman, and Wayne Thiebaud. About half the participants ($N = 22$) reported having known some of the artists and/or paintings previously. An average of 1.43 artists ($SD = 2.19$) were reported as having been known previously, and there were two participants reported having known more than 7 of the artists.

Design. The design of the study phase – 2 (Order – blocked or interleaved first) x 2 (Condition – blocked or interleaved) x 4 (Quartile) x 3 (Number of Exemplars – 12, 15, 18) – was identical to Chapter 2.

The tests were counterbalanced and designed as follows: 2 (Order – blocked or interleaved first, based on which condition participants studied first) x 2 (Condition – blocked or interleaved) x 2 (Exemplar shown – old or new) x 2 (Artist name displayed – right or wrong). The dependent variables of interest were: 1) proportion mind wandering at study, 2) old/new recognition, and 3) artist or category recognition. The measure of inductive learning, here, would be when participants correctly identified the artist for *new*, unstudied paintings.

Artists and the order of conditions were yoked and counterbalanced across participants in the same fashion as in Chapter 2.

Procedure. Participants first studied pairs of artists and paintings in either the blocked or interleaved condition, were tested on their learning, and then studied the remaining artists and paintings in the other condition before one final test. Again, the study phases were identical to

Chapter 2. Participants were presented with pairs of artists and paintings at a rate of 3000 ms with a 1000 ms ISI while being randomly probed for their attentional state.

Test Phase. During the test sessions, participants were shown paintings, one at a time, and asked to evaluate whether they were previously studied or not, as well as categorize the artist whom they believed painted the painting. A painting was presented on screen and participants were asked whether it was "old" (e.g., studied) or "new" (e.g., unstudied, never presented). After their response was made, an artist name was displayed below the painting and participants were asked to judge whether the artist whose name was displayed was "correct" or "incorrect." Participants were tested with 4 paintings from each artist, 2 of which were old and 2 of which were new. Among the 4 paintings, 2 of them were then paired with the correct artist name and 2 were paired with an incorrect artist name. This resulted in 4 different pairings: 1 old painting with the right artist, 1 new painting with the right artist, 1 old painting with the wrong artist, and 1 new painting with the wrong artist, for a total of 96 images tested, 48 per condition. These pairings of paintings and artist names were randomized throughout the test session. Participants could take as much time as they wanted to on the test, and no feedback was provided.

Results

One participant was removed from the ERP analyses (because their EEG data had too many unusable channels), but behavioral analyses computed with them removed did not differ. All analyses were first computed with Order, however, because no main effects or interactions involving Order reached significance, all analyses are reported collapsing over Order. For brevity, only significant results are reported, unless they directly tested the hypotheses.

The statistical procedures were identical to those in Chapter 2 and 3, where appropriate.

Behavioral Results

Old/New Test. Comparisons between interleaved and blocked conditions were performed on three different measures of performance were used to assess performance on the old/new test: (a) proportion of "old" responses, (b) old/new recognition accuracy, e.g., proportion of old images correctly identified as old and new images correctly identify as new, and (c) *d'*. *d'* was computed from the rate of hit rates and false alarms as a measure of sensitivity of whether participants were more likely to respond "old" when an image was actually "old" as opposed to "new".

A 2 (Condition) x 2 (exemplar – old or new) revealed that participants responded "old" more frequently when the image was, indeed, old, $F(1, 39) = 164.98$, $p < .0001$, $\eta_p^2 = 0.81$ (see Figure 4.1). There was no effect of Condition, nor was the interaction between Condition and exemplar significant. A 2 (Condition) x 2 (exemplar) analysis on old/new recognition accuracy revealed that participants were marginally better at recognizing previously studied paintings compared to unstudied paintings, $F(1,39) = 3.66$, $p = .063$, $\eta_p^2 = 0.09$. There was no effect of Condition nor was there an interaction between Condition and exemplar tested. Finally, an analysis of sensitivity, as measured by *d*', revealed no difference between Conditions, $t(39) = 0.71$, $p = .48$, 95%CI[-0.08, 0.17].

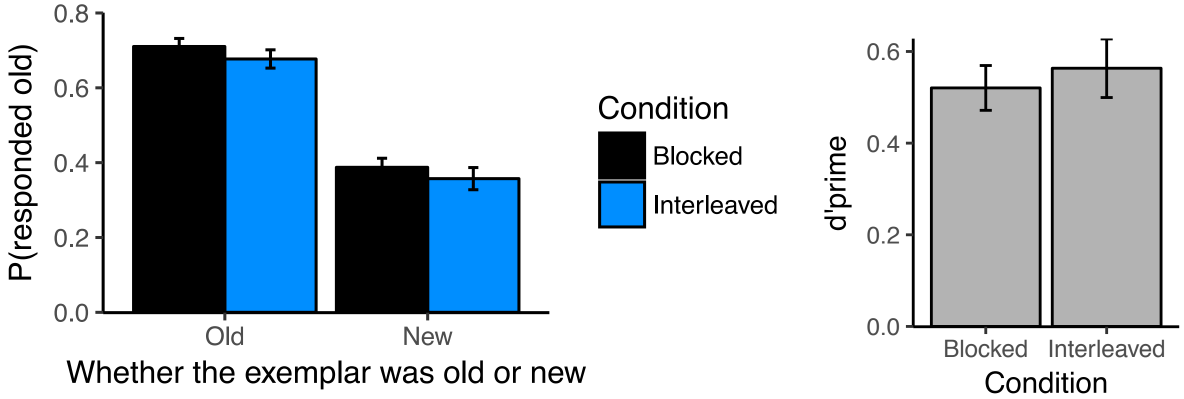

Figure 4.1. P(responded old) and d’ on the old/new test

Proportion responded old (left panel) and d’ (right panel) between blocked and interleaved conditions. Error bars represent standard errors of the mean.

Category Recognition. As shown in Figure 4.2, there was an effect of Condition, $F(1,39) = 70.48$, $p < .0001$, $\eta_p^2 = 0.64$, such that participants were more accurate at identifying the artist for paintings they had studied in the interleaved than blocked condition. There was no effect of whether the item had been previously studied (old) or not (new), nor did it interact with Condition.

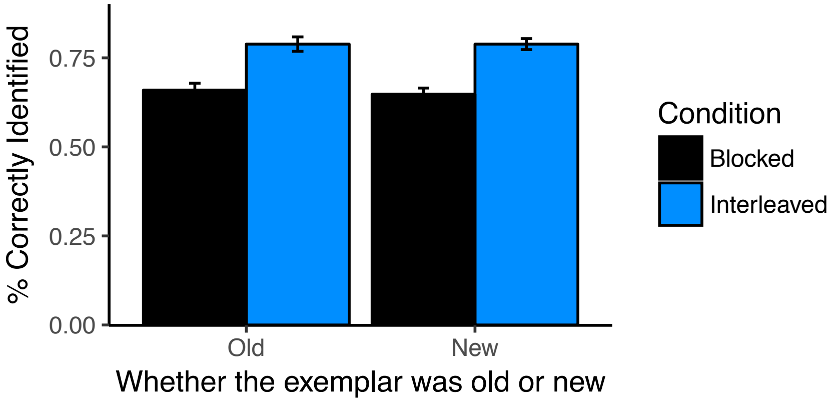

Figure 4.2. Category recognition by condition

Category recognition based on Condition and whether the painting tested was studied (old) or unstudied (new) previously. Error bars represent standard error of the mean. Inductive learning is represented by the right-hand set of bars for the new, unstudied images.

It was impossible to determine whether participants had actually learned the category on trials in which they correctly rejected the incorrectly-paired artist name. Participants could have correctly rejected the trial because they knew the incorrectly-paired artist whose name was presented, but not the identity of the correct artist. Thus, an additional analysis was conducted on trials in which only the *correct* artist name was presented (see Figure 4.3). There was an effect of Condition, such that participants were better able to recognize the artist when the exemplar paintings of those artists had been studied in the interleaved rather than in the blocked condition, $F(1,39) = 38.16, p < .0001, \eta_p^2 = 0.49$. There was also a main effect of whether the exemplar was previously studied or not, $F(1,39) = 12.29, p = .001, \eta_p^2 = 0.24$. Participants were better at recognizing the artists of paintings they had studied previously compared to new never-studied exemplars. The interaction of Condition and Exemplar was not significant.

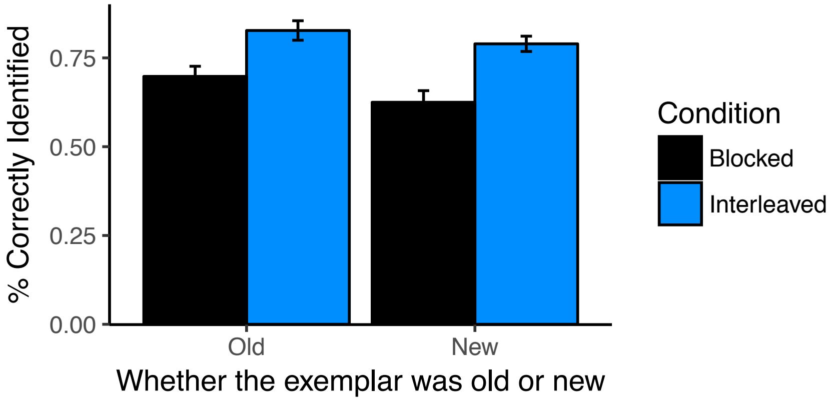

Figure 4.3. Category recognition when the correct category label was tested

Category recognition based on Condition and whether the painting tested was studied (old) or unstudied (new) previously. *Only exemplars which were paired with the correct category label (e.g., artist name) are included*. Error bars represent standard error of the mean. Inductive learning is represented by the right-hand set of bars for the new image presented.

Mind Wandering. Participants mind wandered .35 (*SD* = .20) of the time. As was found in Chapter 2, participants mind wandered significantly more in the blocked ($M = .39$, $SD = .22$) than interleaved condition ($M = .30$, $SD = .24$), $F(1,39) = 6.02$, $p = .019$, $\eta_p^2 = .13$ (see Figure 4.4). There was also an effect of Quartile, $F(2.74, 106.77) = 22.00$, $p < .0001$, $\eta_p^2 = .36$, such that participants mind wandered more over time. A separate 2 (Condition) x 3 (number of exemplars) analysis was computed; however, the number of exemplars did not have an effect. None of the interactions between Condition, number of exemplars, and/or quartile were significant.

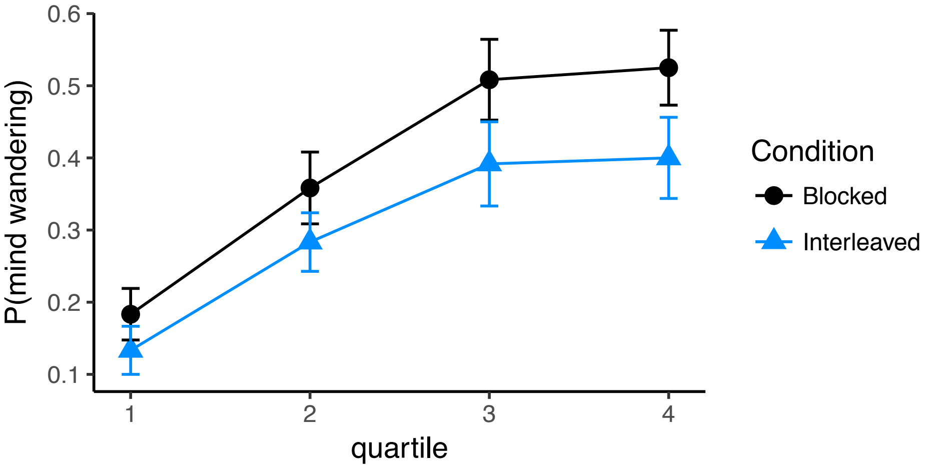

Figure 4.4. Mind wandering by condition over time

Proportion of mind wandering between blocked and interleaved practice over time, as represented by Quartile. Error bars represent standard errors of the mean. There were 3 attentional probes presented within each Quartile.

Mind Wandering and Learning. Between-participant correlations were computed between mind wandering, old/new recognition, and artist (category) recognition, for blocked and interleaved conditions separately. Condition-specific mind wandering scores were computed for each participant and correlated against participants' performance in that particular condition. In the blocked condition, participants who mind wandered more performed more poorly on the old/new test, $r = -.35$, $t(38) = -2.27$, $p = .029$, however there was no effect on artist recognition, $r = -.13$, $t(38) = -0.79$, $p = .434$. On the other hand, mind wandering was negatively correlated with both old/new recognition, $r = -.50$, $t(38) = -3.53$, $p = .001$, and artist recognition, $r = -.58$, $t(38) = -4.35$, $p < .0001$, in the interleaved condition. That is to say, participants who mind wandered more in the interleaved condition were worse at recognizing whether an item was old or new and also worse at recognizing the correct category.

Collapsing across Condition, across the board, participants who mind wandered more performed worse on both the old/new recognition test, $r = -.49$, $t(38) = -3.47$, $p = .001$, as well as the artist recognition test, $r = -.42$, $t(38) = -2.84$, $p = .007$.

Mind wandering and Learning in the Blocked condition. As each attentional state report is tightly linked to a particular artist in the blocked condition, between-participant correlations were not the most appropriate approach for looking at the effect of mind wandering on learning in the blocked condition; a within-participant analysis is required. Therefore, separate 2 (Order) x 2 (Attentional State: on task or mind wandering) x 2 (exemplar: whether the tested exemplar was old or new) mixed ANOVAs on the different outcome measures were computed. Attentional state was treated *as if* it were an independent variable in this analysis. To accommodate the possibility of unbalanced data and the one participant who did not mind wander at all in the blocked condition, additional hierarchical logistic regressions were computed. For brevity, as the pattern of results, unless otherwise noted, were identical, only the statistics for the ANOVA are reported.

As shown in Figure 4.5, participants were more likely to respond "old" for categories in which they reported being on-task in the blocked condition, $F(1,37) = 7.25$, $p = .011$, $\eta_p^2 = 0.16$. There was also an effect of whether the tested item was an old or new exemplar, $F(1,37) = 103.31$, $p < .0001$, $\eta_p^2 = 0.74$. Specifically, participants said that old exemplars were "old" more often than they said new exemplars were old. No other effects were significant.

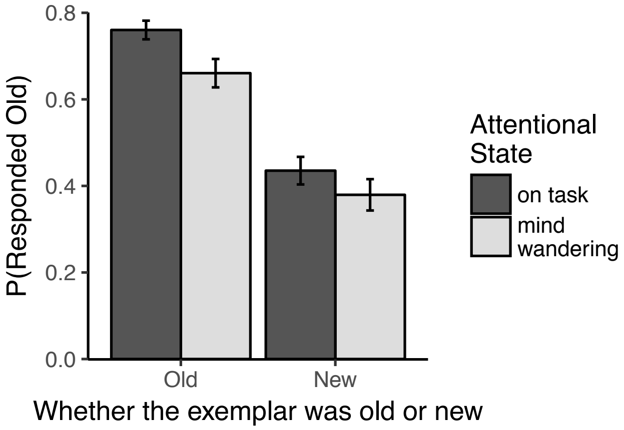

Figure 4.5. P(responded old) by attentional state

Proportion of the time participants responded an exemplar was old (e.g., presented for study previously) given attentional state and whether the exemplar was actually old or new.

A within-participant comparison of old/new recognition accuracy by Attentional State within the blocked condition revealed a main effect of exemplar, $F(1,37) = 9.23$, $p = .004$, $\eta_p^2 = 0.20$, such that participants were better at recognizing previously studied exemplars. While the effect of Attentional State was nonsignificant, $F(1,37) = 0.75$, $p = .39$, $\eta_p^2 = 0.02$, there was a interaction between Attentional State and exemplar, $F(1,37) = 7.25$, $p = .011$, $\eta_p^2 = 0.16$. This interaction was expected given the bias participants had for responding “old” when they reported being on-task. Follow-up Bonferroni-corrected tests revealed that participants were significantly worse at recognizing previously studied items when they were mind wandering, $t(69.87) = 2.65$, $p < .001$, but there was no effect of Attentional State on new exemplars, $t(69.87) = 1.59$, $p < .116$. For those artists participant’s reported being on-task, participants were also better at recognizing whether the item was old or new when the item was, indeed, old, $t(69.10) = 4.05$, $p = .0001$. There was no effect of whether the exemplar was previously studied or not on artists which the participants mind wandered on, $t(69.10) = 0.79$, $p < .434$.[4]

Finally, analyses conducted on category recognition revealed a main effect of Attentional State in the blocked condition, $F(1,37) = 4.64$, $p = .038$, $\eta_p^2 = 0.11$. Specifically, participants

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[4] The logistic regression revealed an additional interaction between Order and whether an old or new exemplar was presented, $\beta = 0.84$, $\chi^2(1) = 5.34$, $p = .021$. Post-hoc tests revealed that participants who studied blocked items second were significantly worse at recognizing new images compared to old images, $z = -3.37$, $p = .0007$; in other words, participants mistakenly responded ‘old’ to never seen before paintings. There was no difference in recognition when participants were exposed to the blocked condition first, $z = -0.30$, $p = .768$. A plausible explanation for this interaction would be that participants who studied interleaved and then blocked items were exposed to twice as many paintings by the time of test, which might have contaminated their learning and decreased their ability to distinguish between those which were previously presented and those which were not. All other effects in the multilevel regression model were identical to the ANOVA.

were selectively impaired in their ability to recognize the works of artists that they mind wandered on. There was no effect of exemplar, nor was there an interaction between exemplar and Attentional State.

Metacognitive Judgments and Self-Report Measures. Consistent with Chapter 2, most participants had fairly accurate metacognitions about their performance. When asked in which condition they mind wandered more, 28 participants said the blocked condition, 9 said the interleaved condition, and 3 said there was no difference, $\chi^2(2) = 25.55$, $p < .0001$. Similarly, when asked in which condition they learned best, most participants said the interleaved condition ($N = 24$), compared to blocked condition ($N = 13$), $\chi^2(2) = 16.55$, $p < .001$. Three reported that interleaved and blocked practice were similarly effective.

Between-participant correlations assessing mind wandering and self-reported ratings on the importance, familiarity, and liking of art are reported in Table 4.2. There was a significant negative correlation between self-reported liking of art and mind wandering, $r_s = -.42$, $p = .008$, such that participants who reported liking art more, mind wandered less. No other correlations were significant. Importantly, while participants self-reported knowing an average1.42 artists ($SD = 2.19$), the number of artists that they claimed to know was not correlated with either their rate of mind wandering or with any test performance measure.

	Importance	Liking	Familiarity	# of Artists Known
Mind wandering	-.11 (.49)	-.42 (.008)	-.24 (.13)	-.22 (.18)
Old/New Performance	.22 (.16)	.14 (.39)	.13 (.44)	.18 (.27)
Category Name Identification	.28 (.08)	.09 (.60)	.09 (.60)	.06 (.70)

Table 4.2. Self-reports, mind wandering, and performance correlations

Correlation matrix of self-reported measures, mind wandering, and test-performance. Spearman rank-order correlations, r_s, were computed because self-reports were measured on a 1-7 Likert scale, with 1 being low importance, liking, and familiarity, and 7 being high importance, liking, familiarity. *P*-values are reported in parentheses.

Event-related potentials

The two questions addressed with ERPs were: (1) whether mind wandering would be associated with attenuations in the late slow wave as seen in Chapter 3, and (2) whether there were processing differences in blocked and interleaved practice during encoding. Analyses focused on 2 different windows: (1) an early sensory P1 from 60-120ms at occipital sites O1, Oz, and O2, (2) an ongoing slow wave from 400-1500 ms thought to reflect deep encoding-related processing at parietal electrodes PZ, P1, P2, P3, P4, P5, and P6 as was done in Chapter 3 (or Xu, Friedman, & Metcalfe, 2018).

Mind Wandering. 2 (Condition: Blocked or Interleaved) x 2 (Attentional state: On-task or Mind wandering) ANOVAs were computed on the two time windows of interest. Degree of freedom may differ as some participants did not report mind wandering in certain conditions.

There was a marginal difference between on task and mind wandering states on primary sensory processing, as indexed by the P1 component, $F(1,30) = 3.40$, $p = .075$, $\eta_p^2 = 0.10$. There was no effect of Condition, $F(1,30) = 0.51$, $p = .481$, $\eta_p^2 = 0.02$, nor was the interaction significant, $F(1,30) = 0$, $p = .997$, $\eta_p^2 = 0$. Analyses computed on the 400-1500 ms window revealed a significant effect of Attentional State, $F(1,38) = 4.27$, $p = .048$, $\eta_p^2 = 0.12$, such that processing was attenuated when participants were mind wandering relative to when they were on-task. There was no effect of Condition, $F(1,38) = 0.12$, $p = .734$, $\eta_p^2 = 0.004$, nor was there an interaction between Condition and Attentional State, $F(1,30) = 0.24$, $p = .629$, $\eta_p^2 = 0.01$.

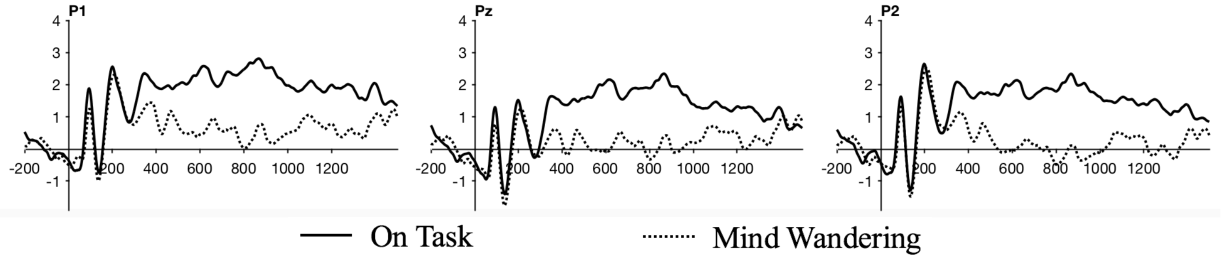

Figure 4.6. On-task and mind wandering ERPs

On task and mind wandering Event-related potentials at the P1, PZ, and P2 electrodes. are shown in the bottom panel. ERPs depicted only included trials in which an attentional report was obtained. Only participants who had on-task and mind wandering reports in both Blocked and Interleaved conditions were included (*n* = 31).

While the interaction between Condition and Attentional State was not significant, to determine whether the interleaving effect might be related to differences in late processing, comparisons of interleaved and blocked practice were performed within on-task and mind wandering states at the 400-1500 ms window. There was no effect of Condition on ERP amplitudes when participants were on-task, $t(59.8) = 0.59$, $p = .557$, or mind wandering, $t(59.8) = 0.69$, $p = .905$.

Single-trial analysis. To account for the lack of mind wandering some participants exhibited, a secondary analysis using single trial ERP data was performed. Single-trial ERPs were extracted and the effects of Condition and Attentional State were examined using a linear mixed-effects model in the R environment (R Core Team, 2013) with the lme4 package (Bates, Maechler, Bolker, & Walker, 2015). Condition and Attentional State were dummy coded and treated as fixed effects within participant. Electrode and participants were treated as random factors. Type II Wald χ^2 tests are reported for main effects and interactions.

There was an effect of Attentional State such that early sensory processing was attenuated when mind wandering relative to when participants were on task, $\beta = 0.72$, $SE = 0.32$, $\chi^2(1) = 6.24$, $p = .012$. There was no effect of Condition, $\beta = -0.16$, $SE = 0.28$, $\chi^2(1) = 0.51$, $p = .476$, or interaction with Condition, $\beta = -0.18$, $SE = 0.49$, $\chi^2(1) = 0.14$, $p = .713$. Single-trial analyses of the late slow wave from 400-1500 ms also revealed an effect of Attentional State such that mind wandering was associated with diminished processing, $\beta = -1.56$, $SE = 0.68$, $\chi^2(1) = 5.57$, $p = .018$. There was no effect of Condition, $\beta = 0.02$, $SE = 0.374$, $\chi^2(1) = 0.003$, $p = .956$, nor was there an interaction of Attentional State and Condition, $\beta = -0.57$, $SE = 0.85$, $\chi^2(1) = 0.45$, $p =.504$. Again, for purposes of the hypotheses, comparisons of Condition within both on-task and mind wandering states were performed. Pairwise Tukey tests revealed no differences between interleaved and blocked conditions when participants were on-task, $t(29.07) = 0.47$, $p = .642$, or when they mind wandered, $t(25.75) = 0.53$, $p = .598$.

Blocked vs. Interleaved. Because only a subset of the data, namely trials at the end of each each block, was used in the previous analyses, additional analyses were conducted with all trials

—— Blocked ·········· Interleaved

to examine the whether there were differences between conditions (see Figure 4.7). There was no difference between conditions at the P1 component, $F(1,38) = 0.63$, $p = .433$, $\eta_p^2 = 0.02$. There was, however, a marginal effect of Condition from 400-1500 ms, $F(1,38) = 3.43$, $p = .072$, $\eta_p^2 = 0.08$, such that ERP amplitudes were greater in the interleaved than blocked condition.

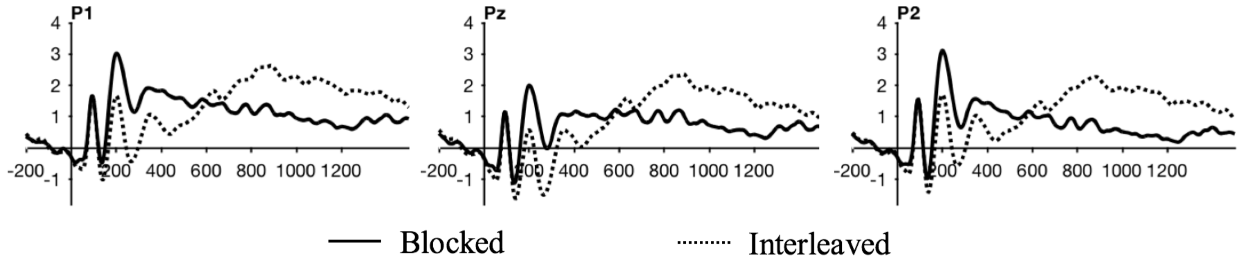

Figure 4.7. Blocked and interleaved ERPs

Event-related potentials for Blocked and Interleaved Conditions at the P1, PZ, and P2 electrodes. The blocked condition is represented by the solid lines and the interleaved condition is represented by the dotted lines. ERPs reflect trials taken across the entire study session from all participants ($n = 39$).

Mind wandering, ERPs, and Learning

To examine the direct relation between the ERP difference found during mind wandering and on task states on learning, a mediation analyses was performed using the bmlm package (Vuorre, 2017; Vuorre & Bolger, 2017). Attentional state was used as the independent variable, single-trial ERP (averaged across electrodes) was the mediator, and binary category recognition performance was the dependent variable. The model is presented in Figure 4.8. ERP amplitude did not mediate the relationship between attentional state and category recognition (indirect effect = -0.001, 95%CI [-0.01, 0.01]; proportion mediated effect = 0.01, 95%CI [-0.12, 0.12]). The effect of attention state on category recognition remained after ERP amplitudes into account (c’ = -0.07, 95%CI [-0.12, -0.03]).

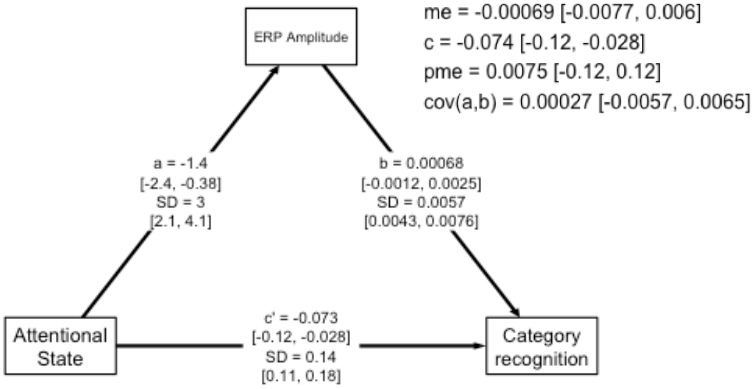

Figure 4.8. Mediation analysis

Path diagram of the multilevel mediation model. Attentional State is coded as 0 (on task) or 1 (mind wandering) based upon participant’s self-reports. c = total effect (direct + indirect effect of X on Y), me = mediated effect, c’ = direct effect, pme = proportion of effect that is mediated, cov(a,b) = covariance of subject-level a and b parameters. Parameters are reported with 95% credible intervals in square brackets.

Discussion

This experiment showed that mind wandering attenuates deep processing and is associated with deficits in learning. The effect of interleaving on reducing mind wandering relative to the blocked condition, found in Chapter 2, was also replicated. Furthermore, these data demonstrated that the memorial benefit of interleaving was specific to category recognition (and induction); there was no difference in old/new recognition between interleaved and blocked practice conditions. (An additional examination into the relation of old/new and category recognition is reported in Appendix 2.) Together, these findings provide converging evidence to suggest that mind wandering results diminished deep, cognitive processing, thereby inhibiting one's ability to learn.

Although the marginal effect of Condition from 400-1500 ms when all trials were included (and differences in processing between attentional states were disregarded) is suggestive of increased processing in the interleaved condition, caution should be taken when interpreting this result. Recall that participants mind wandered significantly more in the blocked than interleaved condition and that mind wandering was linked to poorer recognition and diminished processing. In addition, there were no differences between conditions when ERPs were compared within each attention state or when attentional state was included in the analysis. Insofar as late positivity is an index of encoding-related deep processing, the difference in the rate of mind wandering between conditions could suggest that the observed ERP difference between interleaving and blocking was not due to processing differences between conditions, but rather, differences in the frequency of mind wandering. In other words, participants were less likely to mind wander in the interleaved condition and therefore processed the information to a greater extent. This, then, led to better learning of the materials. In contrast, since learners were more likely to mind wander in the blocked condition, they then processed less of the material deeply and therefore learned worse. To summarize, these data provide an alternate explanation for the benefits of interleaving: the interleaving effect is not due to a difference in condition-specific processing of the materials, but rather a difference in one's ability to remain engaged with the task. Several additional concerns are discussed below.

One limitation of this experiment is the inability to directly model the relation between mind wandering, ERPs, and learning. While an attempt was made with a multilevel mediation, the experimental design precluded proper interpretation of the model. Because items presented for test were sometimes new and sometimes old, it was impossible to directly map a particular artist-painting presented at study (and its associated ERP amplitude) to test performance. Moreover, there were more studied than tested exemplars, making it impossible to evaluate whether and how encoding for the studied but untested exemplars affected test performance. In previous work which utilized a similar analytic approach to examine the relationship between study conditions, ERP amplitude, and recall (e.g., Bloom, Friedman, Xu, Vuorre, & Metcalfe, in press), there was a one-to-one relation between study item, ERP amplitude, and item recall. This relation, however, is not present in this experiment. While an analysis focusing on only the previously studied and tested exemplars might seem like a solution, it is not a viable analytic approach due to the low number of items. To evaluate the effect of mind wandering, only a subset of the presented exemplars – those presented within 12 s of an attentional probe – could be used in the mediation analysis. Furthermore, participants were presumably processing and learning the items which were presented prior to 12 s window. Consequently, although mediation is an encouraging method, for the aforementioned reasons, it is uninformative here. In order to appropriately model the relation of mind wandering, ERPs, and learning, potential experiments would have to present a long sequence of non-repeating items at study, which are all tested later, and have participants randomly report their attentional state throughout. Doing so would overcome the study and test item correspondence problem and allow collection of sufficient data to compute a multilevel mediation.

While the presentation of materials in either a blocked or an interleaved fashion might seem comparable on the surface, there were subtle differences between the two conditions. An attempt was made through counterbalancing and randomizing materials across and within participants and conditions to control for these differences, but they may still have affected ERPs and behavior. These differences include presentation of the category (or artist) name, the visual similarities amongst paintings within each block, and participants' expectations of the subsequent artist-painting exemplar. For example, as the same artist is presented over and over again within the blocked condition after several artist-painting pairs, participants would no longer need to read and process the artist name; they would still need to read the artist name in the interleaved condition though. In particular, item repetition has been shown to have an effect on ERPs. While items in the blocked condition were not identical to one another, they were highly similar. Previous work has demonstrated that presenting the same item again results in suppressed ERP amplitudes related to the initial presentation or non-repeated items (e.g., Grill-Spector, Henson, & Martin, 2006; Gruber, & Müller, 2005). While exemplars in the blocked condition were not identical, they were categorically similar and also repeatedly presented. Therefore, one might predict that ERP amplitudes in the 200-400 ms window, a window affected in repetition suppression effects, would be diminished in the blocked relative to interleaved condition. To examine this, an additional analyses in the 200-400 ms time window was performed. Indeed, there was a main effect of Condition, $F(1,38) = 18.70$, $p < .001$, $\eta_p^2 = 0.33$. Contrary to the expected pattern, ERP amplitudes were *larger* in the blocked than the interleaved condition. It is worth nothing that the repetition suppression effect is characterized by a heightened ERP response to first item of a given category relative to the ERP response to second, or repeated, appearance of the item. Using all the trials in the analysis blurs the distinction between the initial presentation, which should not be suppressed, and repeated presentations, which should be suppressed. While it is possible that repetition suppression might occur in the blocked condition, computation of reliable ERP estimates is difficult as there were only 12 artists per participant per condition. Alternatively, it is possible that no repetition suppression effect exists in the blocked condition. Although items in the blocked condition were visually similar, they were *not* identical copies of the first (or previous) items. Future studies should be conducted to examine whether such an effect exists when items are blocked versus interleaved. Crucially, this difference illustrates an important consideration when examining the efficacy of interleaving. While interleaving might seem like a better alternative to blocking, the underlying mechanics of how and why interleaving works is still not well understood. One possibility for might be through the mind wandering explanation tested here, however, future experiments should also consider alternative possibilities.

In all, these data provide further evidence that the interleaving effect may be due to differences in attention or, more specifically, decreases in the rate of mind wandering. The level of deep processing exhibited during blocked and interleaved practice conditions was similar, however the frequency with which participants' mind wandered within each of these two conditions differed. When people are on-task, blocked and interleaved practice may recruit similar amounts of deep processing. However, because people are unable to remain focused and mind wander at a greater degree during blocked practice, they fail to process the materials deeply and are therefore unable to recognize the items at test.

Chapter 5:

Concluding Remarks

The experiments presented here tackled two broad issues pertaining to mind wandering and learning. The first two chapters of this work were dedicated to understanding causes of mind wandering in hopes of finding ways to reduce the tendency of doing so, and the last two chapters utilized ERPs to examine changes in processing which occurred when one mind wandered during learning. Chapters 1 and 2 identified conditions under which one is more likely to mind wander during learning (i.e., studying materials outside one's own RPL or engaging in blocked practice). By avoiding such conditions, e.g., switching from blocked to interleaved practice, one might then be able to reduce their mind wandering and improve their learning. For example, if a learner were to study materials which tracked their RPL, e.g., items became more difficult as easier materials are mastered, learning efficacy should increase as the tendency to zone out diminishes. Although the reasons why a person might mind wander are manifold and varied, these data demonstrate that altering one's study practices reduces mind wandering and improves learning. Chapter 3 focused on neurocognitive consequences of drifting off task and isolated decreased deep processing as a potential mechanism which may underlie the lack of encoding which goes on during mind wandering. Finally, Chapter 4 replicated the attenuated deep processing result found in the previous chapter while demonstrating the detrimental effect of mind wandering had on learning.

There are several key takeaways from this work. First and foremost, this research underscores the message that there *are* methods to reduce one's likelihood of mind wandering. Two approaches – studying appropriately difficult materials and interleaving (or spacing) materials – were found to decrease mind wandering and were also associated with better learning. While some approaches (e.g., mindfulness training: Mrazek et al., 2013; Schooler et al., 2014; Xu et al., 2017; testing: Szpunar et al., 2013) have also been shown to be effective in reducing mind wandering, more work should be conducted to discover other methods to overcome mind wandering. As people are known to mind wander up to half of their waking moments, changing the rate at which they do so even by five or ten percent could result in tremendous learning gains as well as benefits across other facets of life. Although external influences beyond our control might continue to cause us to zone out, this work demonstrates that it is possible, to an extent, to reduce one's tendency to drift off task.

Second, this research is the first to demonstrate the impact of mind wandering on late ongoing processing (in particular, encoding-related processing). While other studies have demonstrated that mind wandering attenuates early sensory and attentional processing, the effects on learning were yet unknown. The ERP findings presented here were the first to examine and show that mind wandering leads to reductions in late processing, which has previously been associated with encoding or encoding-related processing. While behavioral findings did suggest that encoding was diminished during mind wandering, these experiments were the first to demonstrate this. Not only have Chapters 3 and 4 identified a potential mechanism by which mind wandering impairs learning, but this marker of mind wandering could be used to facilitate the development of neurofeedback tools or paradigms which use brain data to identify when a person is mind wandering (e.g., when the late going slow wave is attenuated) and prompts them to remain on task. There is one important caveat, however. While EEG and ERPs are temporally precise, they are unable to provide accurate spatial localization of where changes in the brain occur during mind wandering and learning. There may be changes in networked regions, (e.g., Golchert et al., 2017; Mason et al., 2007), or other subcortical areas involved. Additional research should be conducted to investigate whether and how being in a mind wandering state affects processing in networked and subcortical regions associated with learning and memory.

Third, this work highlights the role that mind wandering may have on a variety of cognitive and psychological phenomena. For example, these experiments demonstrated that the effect of interleaving on mind wandering might be responsible for the downstream benefits in learning. Because participants were more likely to mind wander in the blocked condition, they were unable to engage with the materials deeply and therefore failed to successfully encode the materials. While interleaving is commonly touted as an excellent study practice for improving learning, the implication that its efficacy is dependent on reducing one's propensity to mind wander is an important one. Merely spacing the materials is insufficient; it must reduce mind wandering in order to boost learning. The role mind wandering plays is not selective to interleaving either. For example, intermittent testing was shown to reduce the incidence of mind wandering (Jing et al., 2016; Szpunar et al., 2016; Szpunar et al., 2016; Szpunar, 2017). These effects – interleaving (or spacing) and testing – might only be the tip of the iceberg; mind wandering could potentially play a vital role in other psychological phenomena. It would behoove the field to more deeply consider the role mind wandering might have on other domains of psychology and related fields. Indeed, if mind wandering is implicated, finding strategies to circumvent or reduce the likelihood of zoning out would be crucial.

Finally, the importance of considering individuals when investigating mind wandering cannot be stressed enough. While Chapter 1 reconciled an important conflict in the literature on task difficulty and mind wandering, it was only possible because individual differences were considered. If expertise was not taken into consideration, the U-shaped pattern of results could have been misinterpreted as people being more attentive to medium-difficulty items. Adding individual-level expertise enabled the separation of non-monotonic effect of task difficulty into two effects: increasing mind wandering as difficulty increased for participants with low mastery and decreasing mind wandering for participants with high mastery. Some have investigated individual differences such as working memory capacity on mind wandering (e.g., McVay & Kane, 2012; Unsworth & McMillan, 2013; Unsworth et al., 2012). However, a more thorough and systematic investigation of individual-level factors is necessary. Not only does it have the potential to reconcile contradictory findings, such as that of task difficulty on mind wandering, but it would further our understanding of these different effects. Future research on mind wandering, and in psychology more generally, should consider factoring in individual participant-level differences where appropriate. Doing so would facilitate a more holistic understanding of the phenomenon in question.

Mind wandering and attention

At first glance, one might consider the construct of mind wandering as the opposite of attention; in other words, a lack of attention. However, this is not necessarily the case. One theory of mind wandering suggests that there are two parallel streams of consciousness that occur simultaneously, one for the external world and one for internal milieu, and that mind wandering happens when one shifts from the external onto the internal stream (e.g., Smallwood & Schooler, 2015; Schooler et al., 2011). In other words, attention becomes decoupled from the external world. Under this framework, attention relates to happenings in the external stream whereas mind wandering deals with the internal stream. When a person mind wanders, they are attending to the internal stream of consciousness instead of the external task at hand.

Even then, skeptics might argue that mind wandering is a particular case of divided attention (e.g., Craik, Govoni, Naveh-Benjamin, & Anderson, 1996; Kahneman, 1973). However, there are clear differences between the two. In divided attention paradigms, attention to the external world is divided to different domains, e.g., visual and auditory, or separate tasks.

The ongoing internal stream of consciousness which is presumably the target of mind wandering still continues to exist. Consequently, an individual would have 3 possible targets to attend to: (1) visual information, (2) auditory information, and (3) their internal thoughts. Divided attention paradigms focus on the first 2 targets whereas during mind wandering participants would be attuned, instead, to their own internal thoughts. This would presumably result in reductions in one's ability to process both visual and auditory information. The impact on the visual and auditory streams of information might also vary depending on the extent that one's mind is focused on their internal thoughts.

The most crucial evidence distinguishing attention and mind wandering comes from neuroimaging studies. If mind wandering is simply a case of inattention, it should be associated with diminished activation of task-related areas and networks. Instead, studies have shown that the contents of and neural processes exhibited during mind wandering are anticorrelated with the external world and instead linked to the default network (e.g., Mason et al., 2007; see Schooler et al., 2011 for review). Moreover, differences in the mode of mind wandering, e.g., intentional vs. unintentional, have been linked to distinct brain regions (Golchert et al., 2017), suggesting that mind wandering is a unique construct with its own neurocognitive marker(s).

Important advances have been made in the last few years to map the relation of mind wandering and learning. Nonetheless, the question of what can be done to prevent or limit mind wandering during learning is still far from resolved. While much research suggests that mind wandering impairs learning (e.g., Metcalfe & Xu, 2016; Smallwood et al., 2007; Thomson et al., 2014; Xu & Metcalfe, 2016), some findings also suggest that specific types of mind wandering may have a positive effect on learning and memory (e.g., Jing et al., 2016; Mason & Reinholtz, 2015). This suggests that the relation between learning and mind wandering is not as simple as a ‘mind wandering = worse learning’ axiom but requires continued research in order to fully elucidate the relation between these two regularly exercised mental activities. Moreover, many questions, such as whether the presence of other learners affects mind wandering or what role mind wandering might have on memory consolidation, remain unanswered. The findings presented here have addressed some of these gaps in understanding and, most importantly, will hopefully serve as a platform for future research on mind wandering and learning.

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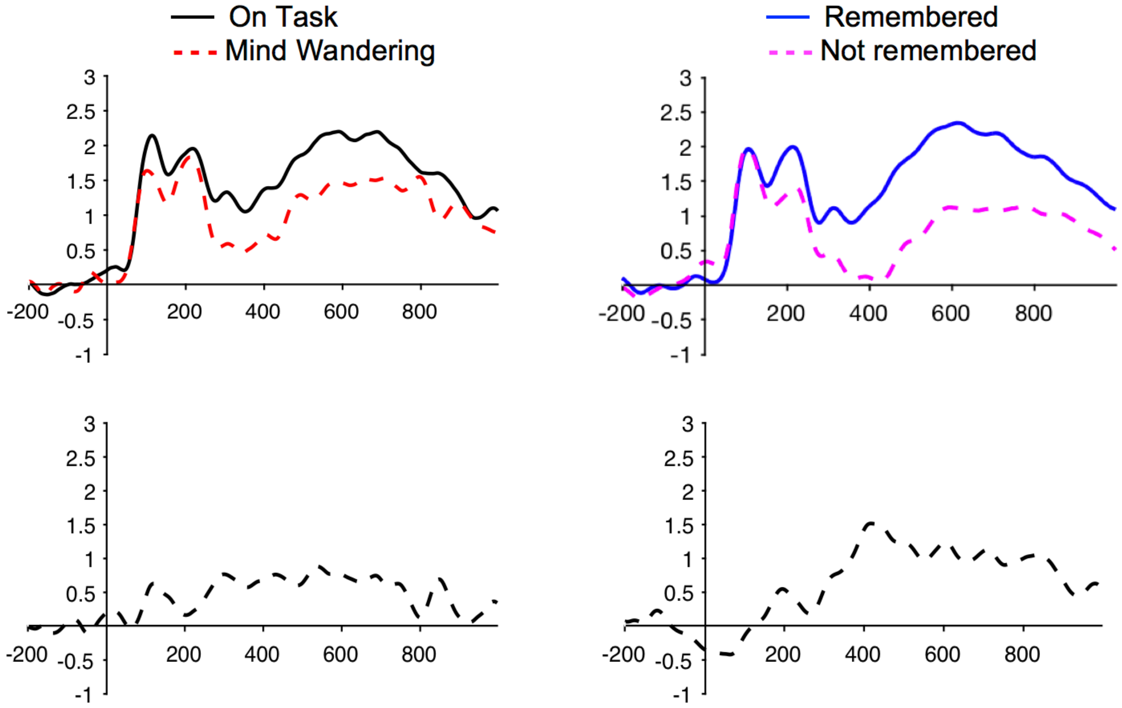
Appendix

Appendix 1

Comparison of the mind wandering attenuation and the Difference in memory (Dm) effect for the PZ electrode in Chapter 3. The left hand side has ERPs and difference waves for On Task and Mind Wandering states, whereas the right hand side illustrates the Dm effect. Dm effect ERPs (and difference waves) were computed from all study trials, whereas the on-task/mind wandering ERPs only include trials which occurred within 12 seconds preceding each respective attentional probe. **Top Row**. On Task trials are represented by the black line and mind wandering trials are presented in the dashed red line. Correctly remembered items are shown in blue and not remembered items are shown in dashed purple. **Bottom Row**. Difference waveforms with the mind wandering ERPs subtracted from the on task ERPs are in the left panel and items not remembered subtracted from remembered items are on the right.



Appendix 2

To investigate the relation between old/new item recognition and category recognition, a hierarchical mixed logistic regression was computed with category recognition accuracy, coded as a 0 or 1, as the dependent measure. Condition (blocked or interleaved), Exemplar (whether the item was previously studied, old, or not, new), Response (the participant's response on the Old/New Test as either old or new), and Artist Shown (whether the correct or incorrect artist name was displayed), were used as factorial fixed effects nested within-participants. *Pr* is used to denote the predicted probability of the respective parameter estimate. The model reported is a non-saturated model with a 3-way interaction among Artist Shown, Exemplar, and Response, and the associated 2-way interactions between the aforementioned factors. The reference in the model was set to previously studied, e.g., 'old', blocked exemplars, which participants responded were 'old' and were presented with the correct artist/category name.

Fixed effects from the model are shown in Appendix 3A. The intercept reflects performance in the blocked condition, averaged across all other variables, suggested that performance was 0.75 with a 95% Confidence Interval (CI) of 0.72 to 0.78. There was a main effect of Condition, $\beta = 0.84$, $SE = 0.11$, $z = 7.94$, $p < .001$, such that people identified more categories in the interleaved (*Pr* = 0.82, 95%CI [0.78, 0.85]) than blocked condition (*Pr* = 0.66, 95%CI [0.63, 0.70]). There was also an effect of Response, such that participants identified more categories which they previously said were 'old' (*Pr* = 0.79, 95%CI [0.75, 0.82]), as compared to items they said were 'new' (*Pr* = 0.70, 95%CI [0.67, 0.74]), $\beta = 0.45$, $SE = 0.10$, $z = 4.40$, $p < .001$. However, as shown in Appendix 3B, the effect of Response was qualified by a significant interaction with Artist Shown, $\beta = 1.70$, $SE = 0.31$, $z = 5.55$, $p < .001$. Follow-up investigations revealed that when the correct category name was given, participants were significantly better at identifying those which they responded were "old" previously, $z = 6.48$, $p < .0001$. There was no difference when the incorrect category name was provided, $z = 2.38$, $p = .017$.

Analyses were also computed with Old/New accuracy in place of Response, but there was no difference. Critically, because response and accuracy were different coding systems for performance, the interaction term of Exemplar and Response, $\beta = 0.32$, $SE = 0.18$, $z = 1.74$, $p = .083$, reflects the effect of Old/New . Modeled category recognition on items in which participants were accurate at identifying as old when old and new when new was 0.76, 95%CI[0.73, 0.80]. It was 0.73, 95%CI [0.69, 0.77] on items in which participants responded incorrectly on the Old/New test.

This pattern of results is in line with the Höffding step (Höffding, 1887, pp. 195-202), which proposed that to remember an association the activation of a memory trace of item A was a necessary step in recalling the associated item B. Here, item A would correspond to the painting and item B would be the category name. Consequently, responding 'old' suggested that participants had activated a memory trace in the same mental space as the correct category name, which then enabled participants to better identify the category later. In contrast, it is difficult to interpret the difference in performance when participants responded 'old' and shown the incorrect category. Participants may have been in the correct mental space, but misled by the presentation of the incorrect category name into thinking it was the correct name. On the other hand, responding 'new' would suggest that a participant was not in the correct mental space of the painting-artist pair, possibly biasing them to say the artist is incorrect. Crucially, memory of who painted the painting isn't required to identify the category; instead, participants may have accurate memory of what the artist lure (or *incorrectly* presented category). As such, they may have used their knowledge of that label to make a judgement of the mismatch between exemplar and category, while not still being unaware what the correct category was. For example, if a participant was presented with an 'Alice Neel' painting and the name 'Terry Winters,' they could provide a correct response if they knew that the painting was *not* 'Terry Winters.' Knowledge of the correct painter – Alice Neel in this case – would not be necessary.

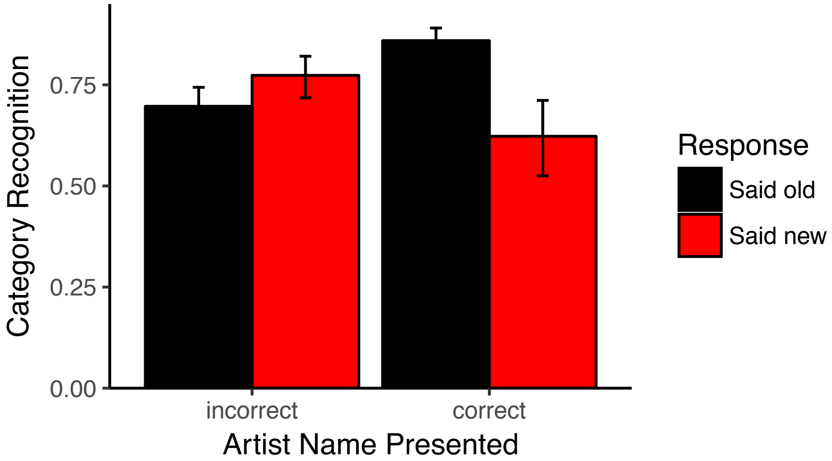
Appendix 2A: Hierarchical logistic regression results

Fixed Effect Parameter Estimates from the Multilevel Model of Category Recognition in Chapter 4. As mentioned previously, all predictors were effect-coded and centered around 0. All factors, except Order, were were nested within participant.

	Estimate (β)	S.E.	*z*-value	*p*
Intercept	0.67	0.78	8.65	<.001
Order	0.07	0.15	0.51	.614
Condition	0.84	0.11	7.94	<.001
Artist Shown	0.13	0.19	0.68	.498
Exemplar	-0.10	0.09	-1.13	.258
Response	0.45	0.10	4.40	<.001
Artist Shown * Exemplar	0.07	0.18	0.38	0.706
Artist Shown * Response	1.70	0.31	5.55	<.001
Exemplar * Response[1]	0.32	0.18	1.74	.083
Artist Shown * Exemplar * Response	0.29	0.41	0.71	.476

[1] The effect Old/New recognition accuracy cannot be directly shown and is represented by the interaction term of Exemplar and Response. For example, saying a previously studied exemplar was "old" or an unstudied exemplar was "new" would be correct/accurate.

Appendix 2B: Modeled category recognition



Model-predicted category recognition performance as a function of whether the correct artist name/category was presented and participant's response on the old/new test. Error bars reflect 95% confidence intervals.