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Short communication

# Monitoring of attentional oscillations through Spectral Similarity Analysis predicts reading comprehension

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ABSTRACT

Deviations of attention from the task at hand are often associated with worse reading performance (Schooler, Reichle, & Halpern, 2004). Ironically, current methods for detecting these shifts of attention typically generate task interruptions and further disrupt performance. In the current study, we developed a method to (1) track shifts of attention away from the reading task by examining the similarity between 5 min of eyes-closed-resting-state EEG and 5 min reading EEG; and (2) investigate, during reading, how the ratio between attention shifts and focused reading relates to readers' comprehension. We performed a Spectral Similarity Analysis (SSA) that examined the spectral similarity between EEG recorded during reading and at rest on a moment-by-moment basis. We then recursively applied the algorithm to the resting-state data itself to obtain an individual baseline of the stability of brain activation recorded during rest. We defined any moment in which SSA during reading was greater than the mean correlation between resting-state EEG and itself as an "attentional shift." The results showed that the proportion of such attentional shifts recorded over the left visual region (O1) significantly predicted reading comprehension, with higher ratios (indicative of more frequent attentional shifts) relating to worse comprehension scores on the reading test. As a proof of its validity, the same measure collected during the reading comprehension test also predicted participants' Simon effect (incongruent - congruent response times) which is a common index of selective attention. This novel method allows researchers to detect attention shifts moments during reading without interrupting natural reading process.

## 1. Introduction

### 1.1. Attention shifts detection tools and findings in reading

Sustained attention over extended periods of time is important in reading comprehensions (Blankenship et al., 2019; Jangraw et al., 2018). For example, both young and older adults who achieved higher scores on sustained attention task performed better on reading task comprehension (Jackson & Balota, 2012). Conversely, reading comprehension decreases during *mind wandering*, a debated construct that indicates intentional or involuntary shifts in attention from a given task or from external stimuli (Christoff, Irving, Fox, Spreng, & Andrews-Hanna, 2016; McMillan, Kaufman, & Singer, 2013; Seli, Risko, Smilek, & Schacter, 2016; Seli, Schacter, Risko, & Smilek, 2017). Although it is not always central to the definition, such shifts typically reflect states in which an individual's attention is directed toward *internally* generated thoughts. In the past three decades or so, researchers have been exploring different tools and paradigms to capture this "flight of mind" and to understand how it affects people's emotion (Killingsworth & Gilbert, 2010), learning (Risko, Anderson, Sarwal, Engelhardt, & Kingstone, 2012; Unsworth & McMillan, 2017), exam performance (Mrazek, Franklin, Phillips, Baird, & Schooler, 2013; Smallwood, Fishman, & Schooler, 2007), and visual recognition (Lutz, Lachaux, Martinerie, & Varela, 2002; see Mooneyham & Schooler, 2013 for a review). In fact, self-reported attention shift frequency is often associated with poorer performance on cognitive tasks (McVay & Kane, 2009; Schooler, Reichle, & Halpern, 2004). Despite its importance, only a few studies to date have investigated attention shifts and their effects on reading, and nearly all of them have relied on self-report or thought probes to identify attention shifts moments during reading (Broadway, Franklin, & Schooler, 2015; Foulsham, Farley, & Kingstone, 2013; Reichle, Reineberg, & Schooler, 2010; Schooler, Reichle, & Halpern, 2004; Smallwood, 2011; Smallwood, McSpadden, & Schooler, 2008; Unsworth & McMillan, 2013).

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Schooler et al. (2004) developed a self-report paradigm to detect readers' shifts of attention during their reading of the opening chapters of *War and Peace*. They first familiarized readers with the concept they called "zoning out"—that is, when readers lost track of what they were reading or found that their thoughts were not related to the text. Then, readers were asked to press a key when they realized they were "zoning out" while reading. Results showed that readers who reported more shifts of attention away from the text also achieved lower comprehension accuracy. Using a similar technique, Unsworth and McMillan (2013) found that such attentional shifts during reading comprehension were predicted by readers' working memory capacity: low-capacity readers reported more attentional shifts away from the text than did high-capacity readers, resulting in lower comprehension scores for the political science texts they were reading. McVay and Kane (2012a) further explored the hypothesis that the relation between working memory capacity and reading comprehension was mediated by executive/attentional control, and in particular to the ability to maintain attention on the task at hand. Using data gathered from multiple cognitive tasks, a structural equation model showed that measures of executive control explained differences in attention shifts between high- and low-working-memory-capacity participants during reading.

Instead of self-reports, Smallwood and his colleagues used comprehension probes at critical and random regions of the text to examine how readers' attention shifts affect their inference-making ability (Smallwood et al., 2008). When reading a Sherlock Holmes detective story, participants were probed during inference critical episodes (section of texts that were relevant to the inference comprehension question) and during random episodes (section of texts that were not critical to generating inferences). Results revealed that readers who had more attention shifts away from the task moments during the inference critical episodes failed to answer the inference question. Interestingly, readers who mind wandered more at the *beginning* of the story also had worse comprehension than those who mind wandered at the end, which is consistent with the greater importance of the initial parts of a text to establish characters and settings.

In addition to self-report, Reichle et al. (2010) investigated attention shifts by comparing readers' eye movement patterns during mindless reading versus engaged silent reading. Participants in this experiment read the entire book of *Sense and Sensibility* in hour-long sessions over multiple days. Researchers explained to participants the concept of "zoning out" and asked them to self-report their mind wandering moments during reading by pressing the "Z" button. Additionally, researchers used a prompt 2–4 min after each self-reported mind wandering moment to check if readers were mind wandering at the time of the prompt. Results revealed that, compared to engaged silent reading moments, mind wandering led to longer fixation durations, fewer regressions, and lower sensitivity to word length and frequency. In other words, although readers' eyes were still fixating on the words, their inattention changed the extent to which they encoded and comprehended the text they were fixating on. Another study also observed similar characteristics of eye movements during mind wandering, showing that when reading sentences that varied in word frequency, mind wandering events were characterized by slower reading speed, longer fixations, and reduced sensitivity to word frequency as compared to engaged reading (Foulsham et al., 2013).

Taken together, these results suggest that accidentals loss of attentional focus during reading decreases the depth of encoding and comprehension of materials encountered. They also show that systematic differences in how frequently an individual mind wanders are related to performance in cognitive tasks that require inference making, working memory, and selective attention.

One challenge with these studies, however, is that all of the methods used to assess whether participants were paying attention to the main tasks also interfere with it in some way (see Gruberger, Ben-Simon, Levkovitz, Zangen, & Hendler, 2011 for a review of methods; Konishi, Brown, Battaglini, & Smallwood, 2017). For example, probes that ask readers to report on their experience (e.g. "Are you focused on the text?") are often delivered during the task, which may interrupt the construction of a situation model as well as other online reading processes. In addition, when readers are asked to monitor their own mind wandering and self-report "zoning out" episodes, they must divide attention between reading and monitoring their own thought processes. This creates a situation akin to dual tasking or divided attention. To make matters worse, the relation between attentional shits and reading comprehension may be mediated by an individual's ability to recover from either the distraction or the need to divide attention between the main task and the monitoring process. To circumvent these limitations, the current study employs a paradigm that measures fluctuations of attention noninvasively using continuous electroencephalography (EEG).

### *1.2. Physiological correlates of attentional engagement*

Acknowledging the limitations of behavioral paradigms, an increasing number of researchers have recently investigated possible physiological correlates of various states of attention. For example, using a self-paced reading task, Franklin, Broadway, Mrazek, Smallwood, and Schooler (2013) monitored readers' pupil dilation changes at the same time that they received experience probes asking about their attention to the task (Franklin et al., 2013). They found that larger pupil dilations were associated with moments of mind wandering and distraction from reading; however, when using pupillometry to investigate mind wandering during other tasks (e.g. a monotonous breath counting task), the opposite finding was demonstrated (Grandchamp, Braboszcz, & Delorme, 2014). These conflicting results suggest that pupillometry may not be a stable physiological measurement for detecting mind wandering during reading.

Researchers have also employed event-related potentials (ERPs) to investigate the neurophysiological correlates of attention during reading and found that the size of the N1 component, a negative peak that occurs 100 ms after the onset of the target word, significantly predicted readers' comprehension (Broadway et al., 2015). However, readers were interrupted 96 times by the thought probes ("Just now, were you mind-wandering?") during the task. Moreover, texts were presented one word at a time at a fixed rate, which makes it hard to explore natural reading processing that usually involve regressions and saccades.

In addition to ERPs, quantitative EEG has also been used to explore the neural markers of attentional engagement (e.g. Braboszcz & Delorme, 2011; Macdonald, Mathan, & Yeung, 2011). Macdonald et al. (2011) observed that participants' attention affected oscillations in the alpha band (8–13 Hz); specifically, high engagement correlated with low alpha power while low engagement led to high alpha power. This finding is consistent with the body of literature showing that increased alpha power, especially over posterior regions, is associated with relaxation and lack of visual processing (Romei, Rihs, Brodbeck, & Thut, 2008). Similarly, Braboszcz and Delorme (2011) found that the moment when participants realized they were off-task and their mind was wandering, power in power in the alpha (9–11 Hz) band decreased. In addition, however, they also found that, when participants recovered from mind wandering, power in the beta (15–30 Hz) band decreased as well, while power in the theta (4–7 Hz) and delta (2–3.5 Hz) bands increased. Taken together, these findings suggest that mind wandering is associated with broad changes across the different electrophysiological frequency bands.

### *1.3. Resting-state brain imaging and mind wandering*

Because EEG and ERPs have limited spatial resolution, a number of other researchers have investigated the neural underpinnings of mind-wandering using other methods. In a landmark study, Christoff, Gordon, Smallwood, Smith, and Schooler (2009) adapted an experience-probing paradigm in a fMRI study. While participants performed a go/no-go attention task, a thought probe was randomly presented to collect their mind wandering information about (1) Whether their attention was on-task or off-task; and (2) If they were aware of their being off-task and mind wandering (note that individuals might or might not be unaware of own their mind wandering, and unaware mind wandering led to worse performance than aware mind wandering; Smallwood, McSpadden, & Schooler, 2007; Smallwood et al., 2008). The results showed that self-reported mind wandering episodes showed increased activity in the medial frontal, posterior cingulate, and temporoparietal cortices, that is, the network of regions collectively known as the Default Mode Network (DMN). There were no activation differences between the meta-awareness mind-wandering moments and those in the absence of meta-awareness, suggesting that mind wandering recruits similar brain regions no matter participants are aware that they mind were wandering or not. Other researchers have reported the similar activation of default network regions during task-independent thoughts, which also considered as mind wandering (Stawarczyk, Majerus, Maquet, & D'Argembeau, 2011).

The association between mind wandering and the DMN provides clues as to the nature of mind wandering and the states that elicit it. The DMN emcompasses a set of regions that are consistently deactivated during performance of experimental task (Christoff et al., 2009; Mazoyer et al., 2001; Raichle & Snyder, 2007; Shulman et al., 1997). Further research showed that these brain regions that were consistently deactivated during cognitive tasks or goal-directed behaviors were also activated during resting state periods, during which participants are not asked to do anything in particular (Raichle et al., 2001; Mason et al., 2007; See Raichle & Snyder, 2007 for a review). Note that, although the neuroimaging literature refers to recordings made of participants lying in the scanner while “doing nothing” as “resting state”, the term does not imply that the participants’ minds are neither empty nor peaceful (Christoff, Ream, & Gabrieli, 2004). Instead, researchers posit that intrinsic activity in the DMN may represent spontaneous, unconstrained, and not goal-directed thought, such as mind wandering, or stimulus-independent thoughts (Christoff et al., 2004; Mason et al., 2007).

Although EEG provides no direct way of measuring DMN activity, the fMRI research strongly suggests that “resting state” periods provide a way to naturally elicit the spontaneous fluctuation of thought that underlie mind wandering. For this reason, this study will examine mind wandering by comparing resting-state EEG with EEG recordings obtained during an active, goal-directed reading task.

### 1.4. Identifying attention shifts through spectral similarity analysis

To investigate the electrophysiological correlates of attentional shifts during reading, we borrowed methods that had been previously developed and successfully applied to fMRI data. In the context of fMRI, two competing approaches have been used to study and decode specific human brain states —machine learning-based *classification* (Norman, Polyn, Detre, & Haxby, 2006) and *representation similarity analysis* (RSA: Kriegeskorte, Mur, & Bandettini, 2008). In essence, classification methods employ supervised learning methods to discover data features that are most predictive of certain mental states, while RSA relies on the similarity between brain responses associated to different states or stimuli. Of the two families, classification-based methods have been used the most, for example, in EEG-based brain-computer interfaces (Rao, 2013). Representation similarity analysis, however, has specific advantages. In particular, it provides a continuous metric (similarity between mental states) that can be generalized across mental states and across individuals and can be applied to small amounts of data. Furthermore, classification is sensitive to optimal feature selection (with generalization decreasing when too many features are selected), while representation similarity analysis can easily accommodate large numbers of features.

Based on these considerations, we developed a new algorithm that detects oscillations in attention. As a benchmark, the algorithm uses characterizations of individual reader’s electroencephalographic (EEG) data obtained from a 5-minute, eyes-closed, resting-state recording as a representative sample of off-task mental state. This variant of RSA, which we call Spectral Similarity Analysis (SSA, in analogy to RSA in fMRI data analysis) involves a continuous comparison of the moment-by-moment spectral characteristics (the percentage of signal explained by oscillations in individual frequency bands) of a neural time series against the spectral fingerprint of the “reference” data obtained during the eyes-closed, resting state period. The basic assumption of this method is that the more engaged in a task an individual is, the more dissimilar his or her EEG will be to the resting-state reference; whereas the less engaged an individual is in a task (e.g., during mind wandering moments) the more similar his or her EEG will be to the resting-state data. Thus, our algorithm provides a continuous metric over time instead of discrete categories at sparse time samples.

As noted above, we used resting-state EEG as our benchmark because it best captures our participants' mental states while they are not engaged in any specific task. It also seems to share the spectral characteristics that have been previous associated with mind wandering (such as increased alpha power and decreased theta power), and, most importantly, it provides an individualized baseline that accounts of individual variations of spectral characteristics across individuals. In fact, previous research has shown that resting-state EEG captures significant amounts of individual variability in cognitive functions (e.g., Gou, Choudhury, & Benasich, 2011; Prat, Yamasaki, Kluender, & Stocco, 2016). For example, researchers have found that young children’s gamma power at rest significantly correlated with their later language development and they argued that high gamma power during resting-state indexed better attentional control and easier access to working memory (Gou et al., 2011). Recently, researchers found that resting-state EEG significantly predicted bilingual adults’ L2 language acquisition speed—resting-state EEG explained 60% of the variability in L2 learning (Prat et al., 2016). Thus, resting state data provides *both* a way to induce and measure mind-wandering activity *and* to characterize individual differences in neural activity.

The use of resting-state EEG as a benchmark also alleviates another complication of this research–namely, the fact that it is difficult to experimentally detect attention shifts non-invasively. This is, in fact, one of the obstacles to the application of machine-learning classification methods to mind-wandering research: the use of probing paradigms tends to yield few reliable samples that can be used as the ground truth for training a classifier. Furthermore, the use of within-task probes might alter the way participants perform the task, thus obscuring some of the data. In contrast, in our method mind wandering is elicited during resting state, and the moment-by-moment similarity of task-based EEG to resting states provides clues to possible shifts of attention without the need to interrupt a task. As a matter of fact, in this study we will report data collected from an *unmodified* standard reading comprehension test, the Nelson Denny Reading Test (Brown, Fishco, & Hanna, 1993).

Capitalizing on this approach, current study aims to (1) compare the spectral similarity between resting-state EEG and EEG obtained during reading on a second by second basis to measure individual differences in the number of times that the two brain states come to resemble one another (i.e., mind wandering moments); and (2) to investigate whether frequency of attention shifts predicts readers’ comprehension during the task; and (3) to see whether attention shifts frequency also relates to executive functioning.

The moment-by-moment spectral similarity between the resting-state EEG and reading EEG provides a stability index of whole brain neural responses at a given moment during reading. Based on the previous literature (e.g. Feng, D’Mello, & Graesser, 2013), we hypothesized that attention shifts should significantly correlate with readers’ performance—a high attention shifts ratio should yield worse reading comprehension. We also hypothesized that the attention shifts ratio during reading should significantly correlate with readers' performance on the Simon task, which reflects' people' executive control abilities, because previous literature has reported that both children and adults' executive control abilities correlated with reading abilities (Blair & Razza, 2007; McVay & Kane, 2012a; Yamasaki & Prat, 2014) and attention shifts significantly correlated with people's executive control abilities (McVay & Kane, 2009, 2010, 2012b).

## 2. Results

### 2.1. Behavioral results

As in previous studies, considerable variability was observed in reading comprehension ability. Participants read 286.32 words per minute on average (range = 106–581, *SD* = 92.88) and their average Nelson-Denny percentile score was 78.92 (range = 16–99, *SD* = 21.45). Individual differences were also observed on the Simon task, with participants showing an average Simon effect (Incongruent - Congruent reaction times) of 57.47 ms (range = −30.39-147.22 ms, *SD* = 37.39 ms). Participants' comprehension accuracy was significantly correlated with their reaction times of the Simon effect ($r(65) = -0.38, p < 0.01$): good comprehenders tended to have smaller Simon effects, suggesting they have greater executive control.

### 2.2. EEG results

EEG data were analyzed using R software (Version 3.3.2). The result of this analysis is a continuous metric, in which peaks denote moments in which attention is maximally off-task. An "attention shift ratio" was calculated as the proportion of peaks that was above the baseline (see Materials and Methods for further details). The number of peaks above the baseline ranged from 0 to 28 (Mean = 7; SD = 8) and the total number of peaks also ranged from 0 to 28 (Mean = 15; SD = 7). Table 1 presents the means and standard deviations of peaks above baseline and total peaks during reading at each channel. Fig. 1 illustrates examples of SSA waveforms from a proficient (99th percentile) reader on the left and a poor (60th percentile) reader on the right recorded over O1.

We further examined whether the attention shifts ratio predicted the participants' reading comprehension performance. The results showed that the attention shift ratio at the O1 channel significantly predicted readers' comprehension accuracy [$r(65) = -0.33; p < .01$]. That is, good comprehenders' attention shifted less frequently and less dramatically than the poor comprehenders' during reading. A greater density of attention shifts above baseline led to worse comprehension performance (Fig. 2A). The total number of peaks did not correlate with comprehension ($r(65) = -0.07; p = .53$).

To test whether our measure also co-varied with a behavioral measure of executive function, we examined the correlation between the mind-wandering ratio and the Simon effect (that is, the difference between response times in incongruent and congruent trials; the smaller the effect, the better the executive functions). As expected, the mind wandering ratio also significantly correlated with the Simon effect [$r(65) = 0.4; p < .001$] at the O1 channel. Participants whose attention fluctuated above the baseline more frequently during reading tended to have bigger response time differences between the congruent vs. the incongruent trials in the Simon task (Fig. 2b), indicating that readers who mind wandered more frequently had lower executive function.

**Table 1**
Means and Standard Deviations (SD) of attention shifts peaks and total peaks during Nelson Denny Reading at 14 channels.

| Channel | Total Peaks | | Mind Wandering Peaks | | Mind Wandering Ratio |
|---|---|---|---|---|---|
| | Mean | SD | Mean | SD | |
| AF3 | 15 | 7 | 6 | 8 | 0.43 |
| AF4 | 14 | 8 | 7 | 8 | 0.56 |
| F3 | 16 | 8 | 6 | 8 | 0.38 |
| F4 | 16 | 6 | 7 | 8 | 0.47 |
| F7 | 13 | 7 | 10 | 8 | 0.74 |
| F8 | 13 | 7 | 9 | 8 | 0.66 |
| FC5 | 15 | 7 | 9 | 8 | 0.57 |
| FC6 | 15 | 8 | 8 | 8 | 0.56 |
| O1 | 16 | 7 | 6 | 8 | 0.35 |
| O2 | 16 | 7 | 5 | 7 | 0.28 |
| P7 | 17 | 6 | 8 | 8 | 0.48 |
| P8 | 18 | 5 | 6 | 7 | 0.31 |
| T7 | 16 | 7 | 11 | 8 | 0.66 |
| T8 | 17 | 6 | 9 | 8 | 0.52 |

## 3. Discussion

The goal of this study was to: (1) develop a method to detect readers' attention shifts during reading without interruption, (2) investigate how the frequency of on-task attention shifts (the attention shift ratio) affected readers' comprehension, and (3) examine whether the attention shifts ratio relates to executive functioning. We have attempted to operationalize attention shifts and measure their impact on reading without interrupting the natural reading process. Our SSA analysis found that the number of times an individual's brain state during reading closely resembled their brain state during rest, as measured through spectral analysis of EEG data recorded over the O1 channel, predicted their comprehension accuracy on the Nelson Denny Reading Task. Specifically, better comprehenders had fewer moments in which reading EEG resembled resting-state EEG than did poorer comprehenders. Although we did not confirm behaviorally that individuals were mind wandering during these points, our results replicate previous findings that more attention shifts moments lead to worse performance in a reading task (Feng et al., 2013; Schooler et al., 2004).

Despite its promising results, our experiment is not without limitations. One of these limitations is that we don't yet have a "ground truth" (i.e., events that can be unambiguously labeled as distractions or mind-wandering moments, for example) that establishes a link between SSA and fluctuating cognitive states. However, additional evidence suggests that our SSA does relate to attention; for example, individual differences in attention shifts peaks ratios were also related to a canonical measure of selective attention, the Simon task. Readers who exhibited better attention control in the Simon task achieved higher comprehension accuracy. Their attention shifts ratio during reading also significantly correlated with their performance on the Simon task. This finding is consistent with the results reported by McVay et al. (2012a), showing that mind wandering was a significant mediator between reading and attention control, and that frequency of mind wandering was significantly correlated with both. Interestingly, a recent fMRI reading study (Hsu, Clariana, Schloss, & Li, 2019) showed that readers with higher electronic device usage showed reduced BOLD activity in parts of the attentional shifting network (e.g. left insula and *pars triangularis* of the inferior frontal gyrus). The authors suggested that greater usage of electronic devices might decrease sustained attention, which, in turn, leads to inefficiencies in coordinating cognitive resources and switching between the central executive and the default mode network.

In terms of evaluating our measure, it is important to note that the fluctuation of mental states peaks detected by SSA were most related to reading at the O1 location. This may be because the larger alpha peaks in posterior regions during eyes-closed resting state allow the most specific characterizations of mental states (Pollen & Trachtenberg, 1972; Ray & Cole, 1985). Alpha power has been previously reported to be related to attentional engagement/disengagement (Braboszcz & Delorme, 2011; Macdonald et al., 2011). For example, Macdonald et al. (2011) has found that participants' alpha power was significantly correlated with their attentional state ratings—when participants reported

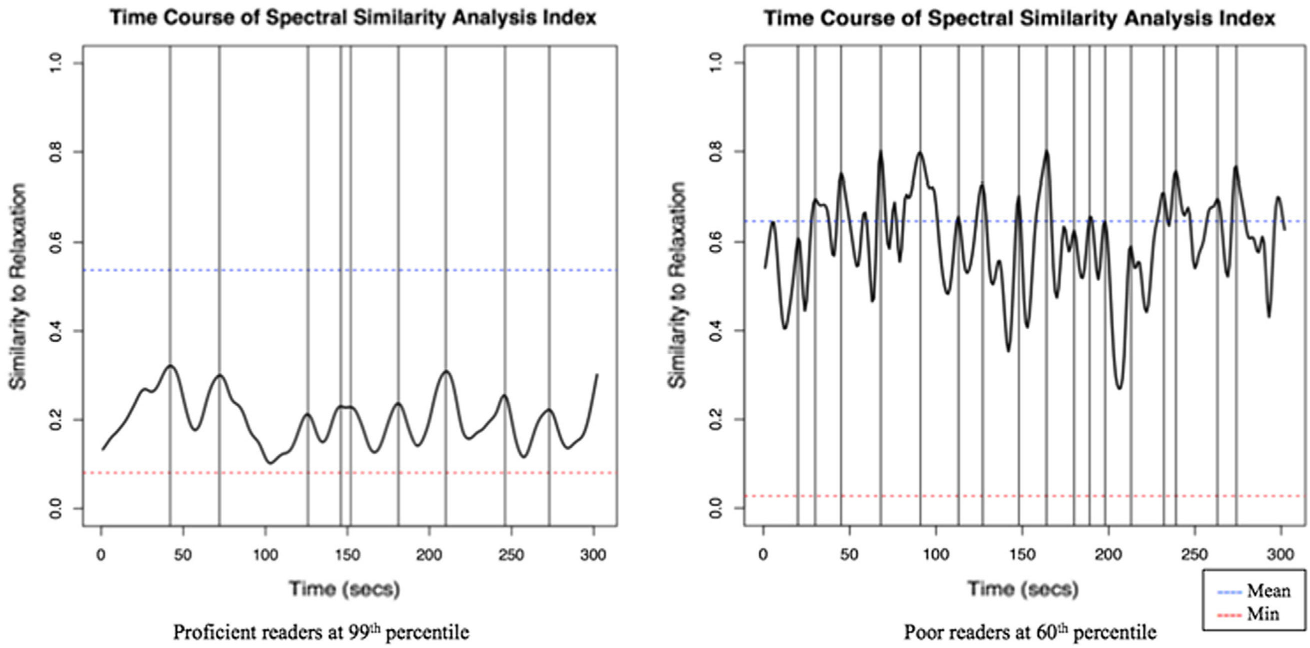


**Fig. 1.** The similarity of spectral composition between resting-state qEEG and Nelson-Denny reading task qEEG of a proficient reader at 99th percentile (left) and a poor reader at 60th percentile (right).

themselves highly engaged in the task, lower alpha was observed while lower attentional state rating was associated with higher alpha power. Thus, it is not surprising that we found that the mind wandering ratio at O1 significantly predicted the reading comprehension accuracy and the Simon effect.

It is also important to note that we only recorded EEG during the first five minutes of the reading task. Thus, the actual correlation between reading performance and attention shifts ratio detected from our method may increase if we recorded EEG during the entire test. However, one previous study has found that moments of distraction (recorded as mind wandering events) at beginning of a text impairs comprehension more than at the end of a text (Smallwood et al., 2008). Thus, the first 5 min of reading may be the most reliable segment to predict reading comprehension.

Although this study aims to detect attention shifts without interruption, one critical limitation is that we don't have a clear understanding of the cognitive states that are reflected by these deflections in brain activation. Readers may take their attention away from the current text for different reasons. For example, they might be distracting themselves from the current portion of a passage to (1) retrieve information from an earlier part of the passage, or (2) thinking about something entirely irrelevant to the text (e.g., "what's for lunch"). It is plausible that both of these "flights of thought" yield similar spectral patterns. However, one might predict that readers who queried the discourse model more frequently would have *better* comprehension performance; whereas readers who were querying the "What's for lunch" model should have worse performance. Our data suggest the latter relation, but without subsequent testing, it is impossible to tell whether our data contain some combination of these two mental processes. Future research can manipulate the information presented in texts and the content of subsequent comprehension questions to resolve which one of the two reasons cause the spectral deviations. Finally, our results are limited by the technology used, and in particular by the use of low-density headsets. Using higher-density headsets would likely increase the quality of our recordings, and open up the opportunity of extending our algorithm to the entire set of channel recordings across

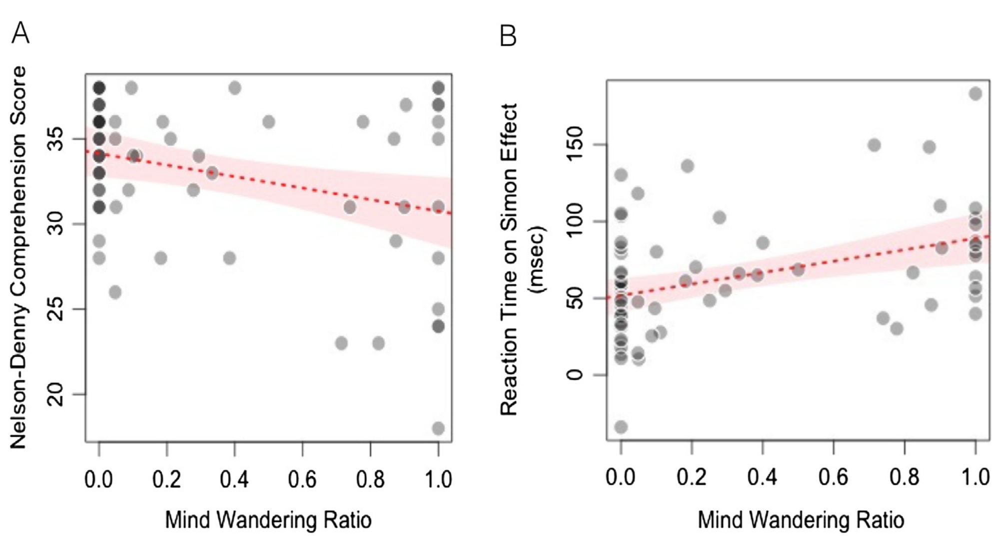


**Fig. 2.** The scatterplot between attention shifts ratio and Nelson-Denny Reading Comprehension accuracy (A) and individual Simon effects (B).

the scalp.

Despite these limitations, our novel SSA method successfully captured variability between participants, and this variability was related to attention and reading in systematic ways. Thus, we believe that this method has potential that warrants future applications for mind wandering and attention research. Specifically, this method can be used to detect participants' mental states based on their real-time EEG data without interrupting their natural behaviors. Its adoption could advance our understanding of how people's mental states change when performing different cognitive tasks, and how the dynamics of these changes affect concurrent or subsequent performance. It might also have potential great implications for improving people's performance in tasks that need instant correction, i.e. driving and learning. Failing to maintain sustained attention may lead to fatal consequences in driving; in an educational context, mind wandering may lead to slow learning speed and lower learning achievement. With our method, researchers can detect attention shifts moments and provide real-time alerts to drivers and learners when mind wandering is detected, which will potentially boost users' sustained attention on the tasks and lead to better performance and learning achievement.

## 4. Method

### 4.1. Participants

Sixty-seven English monolingual speakers (51 females) aged between 18 and 33 years old (mean = 21) were recruited from the Psychology subject pool at University of Washington in Seattle. They all had normal or corrected to normal vision and they did not have any neurological disorders. They did not take any medication that would interfere with neurological functions. They either receive research credits or cash payments for their participation.

### 4.2. Materials

Participants were recruited as part of a larger language project looking at individual differences in reading and brain responses. Their reading ability, working memory capacity, and selective attention skill were measured through a series of tests. Specifically, the Language Experience and Proficiency Questionnaire (LEAPQ: Marian, Blumenfeld, & Kaushanskaya, 2007) was used to examine participants' language history and verify that they had no significant exposure to a second language. The Simon task (Craft & Simon, 1970; Simon, 1990) was employed to examine individual differences in participants' selective attention. During the task, participants were presented with one of two shapes, either a black square or a black circle, on a white background. Participants were instructed to respond to one shape (e.g., squares) with their right hand, and to the other shape (e.g., circles) with their left hand; the associations between shapes and hands were randomized across participants. Each trial was introduced by an 800 ms fixation, followed by a 250 ms gap, followed by the stimuli. The stimuli remained on the screen for either 3000 ms or until a response was recorded, with a new trial beginning immediately afterward. Each shape could appear on either the left and right side of the screen, thus creating either congruent (e.g., a stimulus associated with a left response and presented on the left half of the screen) or incongruent (e.g., a stimulus associated with a left response and presented on the right half of the screen) trials. As in Stocco et al. (2017), the task consisted of a single block of 64 trials in random order, with 75% of the trials being congruent and 25% of trials being incongruent.

The Nelson Denny Reading Test (Brown et al., 1993) is a standardized paper-and-pencil test for college readers. Only the comprehension portion of Nelson-Denny Reading Test[1] was used in the current study. The comprehension test contains seven reading passages with comprehension probes and lasted 20 min. Participants' comprehension score was calculated as the number of questions answered correctly out of the 38 questions asked. Raw scores were transformed into percentile ranks based on reading scores for 2nd year college students.

### 4.3. Procedures

All participants completed a series of 1–1½ hour long behavioral sessions as a part of a larger study on individual differences in language, learning, and cognitive abilities before the EEG recordings.

### 4.4. EEG acquisition and preprocessing

Continuous EEG were recorded from a wireless 16-channel headsets[2] (Emotiv EPOC, Australia) at a sampling rate of 128 Hz. The reference channels are the so-called DMS and CRL electrodes over the parietal lobe. During the Resting EEG recording session, the experimenter read the following instruction to the participants—"*We are now going to start the recording session, I am going to be turning off the lights for 5 minutes. During this time please remain still, close your eyes, and relax – but remain awake.*" while participants' 5-minutes of resting-state EEG was recorded. During the reading EEG session, participants worked on the Nelson-Denny Reading Test while another continuous 5-minute recording of reading EEG was acquired at the beginning of the task. The reading EEG session was started after the reading rate portion of the comprehension test was complete (e.g., 1 min after the start of the Nelson Denny Reading Test).

### 4.5. Spectral similarity analysis algorithm

Fig. 3 visually presents the SSA algorithm. It uses the raw data from the resting-EEG and from the reading task as inputs for the analysis. The SSA algorithm is the following. We indicate the spectrum of a target time series $Y$ at time $t$ as $S(t)$, and the *reference* time series (i.e., the resting state recording) as $R$. For a continuous signal $Y$, the SSA of $Y$ at time $t$, indicated as $\zeta(t)$, is the Pearson correlation between $S(t)$ and $S(R)$, or cor[$S(t)$, $S(R)$]. Here, $S(t)$ can indicate either the instantaneous spectrogram or the spectrogram of a moving window. To fully characterize changes in attention, one needs to consider not only the frequency of oscillations in similarity, but also their amplitude. To identify a plausible amplitude cutoff, we calculate a baseline value $B$ as the mean expected value of $\zeta(t)$ from $R$ itself, that is, $B = \mathrm{E}[\zeta(t)]$. Then, peaks above the baseline are identified by applying a standard peak detection algorithm (Weber, Ramachandran, & Henikoff, 2014) to the SSA time course in each channel for each subject. Peaks above the baseline, therefore, likely represent moments of attention shifts. The proportion of peaks in $\zeta(t)$ that exceed the baseline $B$ is taken as an index of an individual susceptibility to attention loss and distraction. The SSA R code is available on the github. (https://github.com/manqi11/Spectral-Similarity-Analysis.git)

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[1] The rational to use the Nelson Denny Reading task is that previous

(*footnote continued*)
behavioral study found that readers reported more mind wandering moments in Nelson-Denny Reading task than other easy text (Feng et al., 2013).

[2] Fourteen channels are AF3, AF4, F3, F4, FC5, FC6, F7, F8, T7, T8, P7, P8, O1, O2.

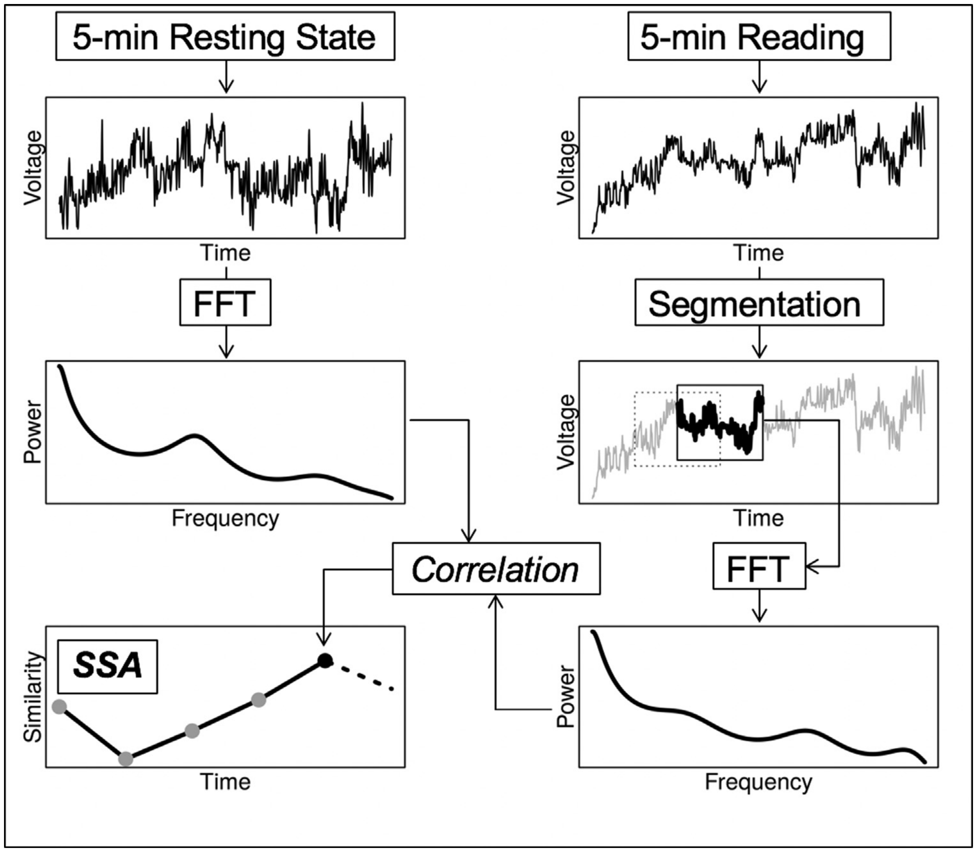


**Fig. 3.** The flowchart for implementing the Spectral Similarity Analysis Algorithm to the resting-state EEG and reading EEG data.

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