Mind the reading mind: a multifaceted and methodologically diverse approach to investigating the role of attentional control and feedback in reading comprehension

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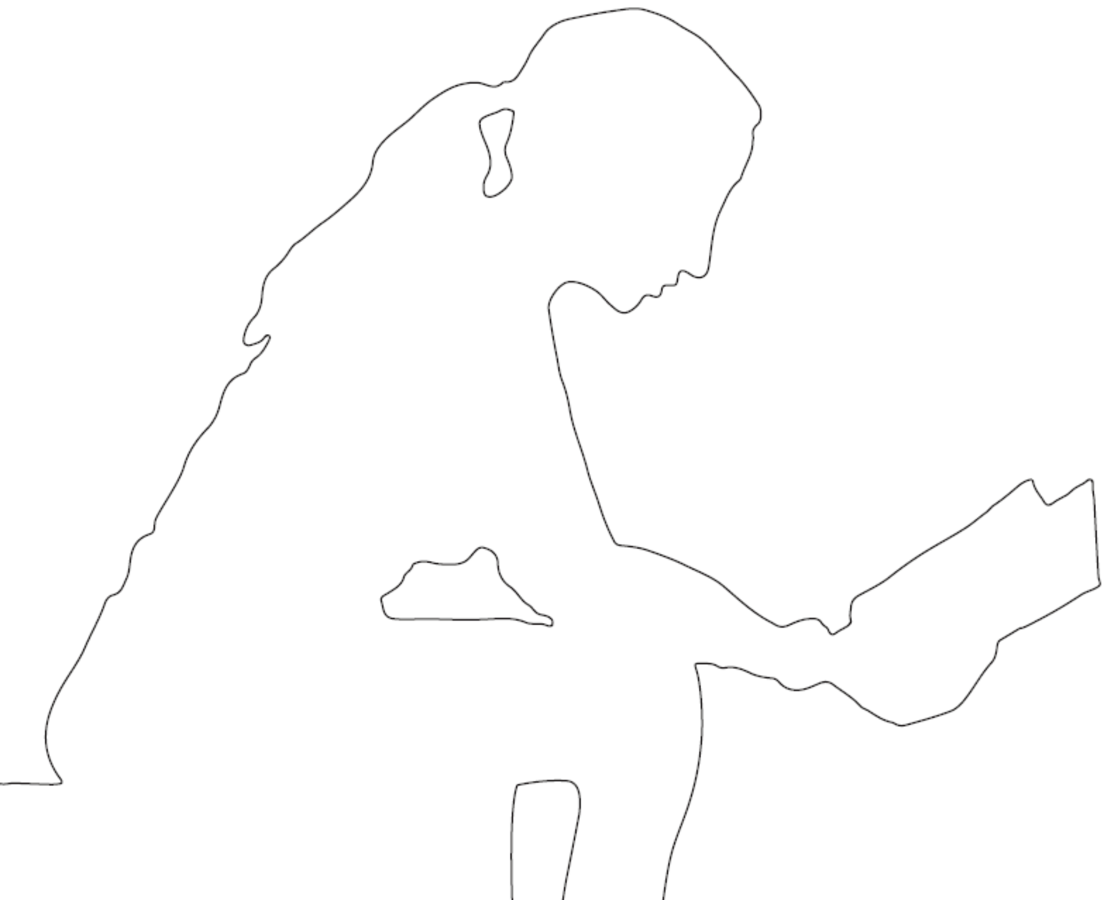

Chapter 2

Frontal Theta/Beta-Ratio (TBR) as Potential Biomarker for Attentional Control During Reading in Healthy Females

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Abstract

The aim of the present study was to expand previous research on the value of frontal theta/beta-ratio as a state measure of attentional control, by applying this measure during reading. Healthy female undergraduate students (*N* = 24) read two texts (with and without nonsense words), self-reported mind wandering during reading and filled in questionnaires about attentional control in daily life. Frontal theta/beta-ratios during the baseline phase and during reading were strongly related. The average frontal theta/beta-ratio during reading predicted reading comprehension of the text with nonsense words and fully mediated the relationship between frontal theta/beta-ratio during the baseline and reading comprehension. Fluctuations in frontal theta/beta-ratio during reading were related to frontal theta/beta-ratio during baseline and to self-reported mind wandering during reading for the text with nonsense words. Results show that frontal theta/beta-ratio is a promising state measure of attentional control during reading. Replication in other samples and with different texts is needed to better understand its potential.

Keywords: attentional control, mind wandering, reading comprehension, EEG, theta/beta ratio (TBR)

Introduction

The ability to accurately read and understand texts is indispensable for academic success. Students are expected to use reading as a tool for subject learning, such as history, chemistry, and foreign language learning. The grammar of these academic texts is complex and information density is high, requiring deep reading to comprehend these texts (LaRusso et al., 2016). In addition to decoding and language comprehension skills (Gough & Tunmer, 1986), deep reading requires the reader to regulate attention in order to continuously select and process information from the text (Arrington et al., 2014; Georgiou & Das, 2016). Research has shown that readers who better regulate their attention during reading have a better understanding of what they have read (Dixon & Bortolussi, 2013; Feng et al., 2013; McVay & Kane, 2012; Reichle et al., 2010; Sanders et al., 2017; Smallwood et al., 2007; Smallwood et al., 2008).

Measuring Attentional Control During Reading

Attentional control during reading is a difficult construct to measure. That is, there is no button that researchers can use to turn attentional control on and off while reading. As a consequence, most research on attentional control during reading uses indirect measures, like self-reports (see also Smallwood & Schooler, 2015). In these studies, participants are asked to report (the frequency of) moments where they failed to control attention, referred to as mind wandering. During mind wandering attention drifts away towards thoughts and feelings that are not relevant to the primary task someone is involved in (Smallwood & Schooler, 2006). During mind wandering people process information in a text they are reading at most on a superficial level (see Reichle et al., 2010; Smallwood, 2011). In studies on mind wandering during reading, probe-questions are most commonly used as a self-report measure. Several times during reading people are asked whether or not they are mind wandering (i.e., if they were experiencing lapses in attentional control). Other methods are asking participants to press a button during reading each time they realize that they are mind wandering (see e.g., Sanders et al., 2017) or retrospectively asking them to report on their attention during reading. Although the number of lapses in attentional control can be informative as an approximation of attentional control, reducing attentional control back to a dichotomous construct (i.e., treating attention as an all-or-none fashion) is an oversimplification. Attention can be controlled both consciously and unconsciously (see e.g., Golchert et al., 2017) and attention to a task can be coupled or decoupled in a hierarchically graded manner (Schad et al., 2012). This means that a reader can gradually lose attention, ranging from low-level decoupling of attention that mainly hinders deep-level processing of information in the text to high-level decoupling level of attention that hinders the reader from deep-level processing and superficial and perceptual level.

Drawbacks of Self-Reports of Lapses in Attentional Control

In addition to the fact that self-reports of mind wandering reduce attentional control to a dichotomous construct, the validity of self-reports as measure for attentional control during reading can be questioned. First, in most studies, texts are presented to participants sentence-by-sentence (e.g., Feng et al., 2013) or word-by-word (e.g., Smallwood et al., 2008), allowing the readers' eyes to only move forward in the text. However, research has shown that readers often fixate more than once on the same word, that 10 to 15% of the eye movements of skilled readers are regressions backward in text (Rayner et al., 2005). The number of regressions are even higher in the case of comprehension difficulties while reading a text (see also Ehrlich et al., 1999). Second, the use of probe questions forces the reader to interrupt reading several times to reflect on his or her mental state to answer the questions with regard to mind wandering. These interruptions may interfere with the construction of a mental model of the text – a representation of the meaning of the text in memory (van den Broek & Gustafson, 1999).

A third drawback of using self-reports arises from the discrepancy between unconscious and conscious moments of mind wandering (see Schooler et al., 2004; Seli et al., 2016). People are not always conscious of the fact that they are mind wandering (Smallwood & Schooler, 2006). Although unconscious moments of mind wandering are considered more detrimental to reading comprehension (Smallwood et al., 2008), these moments may be more difficult to assess using self-reports than conscious moments of mind wandering (Schooler, 2002).

A fourth drawback concerns the content-driven perspective of self-reports of mind wandering. Self-reports reveal something about the content of the readers' thoughts (see Faber & D'Mello, 2018; McVay & Kane, 2010; Smallwood & Schooler, 2006, 2015), but do not provide any information about the underlying processes in the brain (Christoff et al., 2016). Smallwood and Schooler (2006) argued that mind wandering can be seen as a redirection of executive, or attentional, control from the current task to more prominent personal goals and beliefs. According to this reasoning, mind wandering shares the same executive resources as task-related thinking. However, in McVay and Kane's *control failure x concerns* theory (2010) it is stated that mind wandering represents a failure, instead of a redirection, of attentional control to suppress task-unrelated thoughts. They describe task-unrelated thoughts as personal-goal-related thoughts that are continuously and automatically generated by the resting state or default network (DN) in the brain. The executive-control, or attentional control, system needs to prevent task-unrelated thoughts from inferring task-performance. In line with this reasoning, fMRI research showed that lapses in attentional control are related to increased activation in the DN and decreased activation in the frontal brain regions related to attentional control (Moss et al., 2013; Weissman et al., 2007).

The Potential of Using EEG to Measure Attentional Control

One potential method that might add to information obtained by self-reports of mind wandering as an indicator of attentional control would be the use of a biophysiological measure of attentional control during reading. Electroencephalography (EEG) might be a suitable method because it provides an “online” non-invasive measure of brain responses with good temporal resolution. That is, EEG does not interrupt the natural reading process and for capturing lapses in attentional control the reader is not required to be aware of mind wandering. Additionally, a continuous EEG measure is more in line with recent graded views of attentional control (see Schad et al., 2012). Also, combining different types of measures (e.g., EEG and self-reports) might help to expand our understanding of the construct. That is, EEG might help to better understand the processes that occur in the brain during self-reported mind wandering. Taking these considerations into account, in the present study we aim to use EEG technology to test a biophysiological marker of attentional control.

A large base of EEG research on attentional control processes has focused on brain activity in the alpha frequency band (for reviews see Bazanova & Vernon, 2014; Klimesch, 2012; Klimesch et al., 2007). However, research did not result in agreement about what specific index should be used as an indicator for attentional control and results show a mixed picture of the meaning of increases and decreases of alpha activity and its relation to attentional control. Alternatively, EEG-studies into the neural correlates of attentional control have shown that the ratio between slow waves (theta band; 4-7 Hz) and fast waves (beta band; 13-30 Hz) of frontal brain activity, the frontal theta/beta ratio (TBR), can be used as a biophysiological marker for attentional control with higher ratios reflecting lower levels of attentional control and lower ratios reflecting higher levels of attentional control (Aldemir et al., 2017; Angelidis et al., 2016; Barry et al., 2003; Putman et al., 2010, 2014; van Son et al., 2018). For example, children and adolescents with ADHD have higher frontal TBRs in resting conditions compared to typically developing individuals (for a review see Arns et al., 2011). In non-clinical samples, results are more nuanced. In some studies frontal TBRs during resting conditions were positively related to self-reports of attentional control in daily life (e.g., Angelidis et al., 2016; Putman et al., 2010, 2014). Other studies failed to find this relation (Angelidis et al., 2018; van Son et al., 2019a, 2019b). The samples and methodologies used in these non-clinical studies were comparable, except for the type of resting conditions during which EEG was recorded. In two out of three studies in which no relation was found (van Son et al., 2019a, 2019b), EEG was recorded in an eye-closed resting condition, while the previous studies that did find a relation (Angelidis et al., 2016; Putman et al., 2010, 2014) used a combined score for eyes-open and eyes-closed resting condition. Nevertheless, researchers could not explain if this difference in resting conditions could account for the difference in results and stated that replication was needed to clarify the relation between frontal TBR during resting conditions and self-reported attentional control in daily life.

Besides relating frontal TBR during resting states to trait attentional control, some researchers investigated fluctuations in frontal TBR during task performance in relation to state attentional control (Braboszcz & Delorme, 2011; van Son et al., 2019a). Whereas a trait measure is used as an indicator of attentional control in general, a state measure of attentional control should be sensitive to capture meaningful differences, or fluctuations, in attentional control that are influenced by situational circumstances and/or interactions between the person and the situation at a given time point (see also George, 1991). In line with this reasoning, Braboszcz and Delorme (2011) and Van Son et al. (2019a) found increasing frontal theta activity and decreasing frontal beta activity, resulting in an increase in frontal TBR, during periods of self-reported mind wandering compared to on-task periods in a breath-counting task. To the best of our knowledge, the present study is the first in which frontal TBR is investigated as an indicator of state attentional control during reading, which is a more complex cognitive task.

Present Study

The aim of the present study was twofold. On the one hand, we aimed to expand previous research investigating frontal TBR in relation to state attentional control (Braboszcz & Delorme, 2011; van Son et al., 2019a), during reading. On the other hand, we tested whether findings from previous studies, showing that attentional control during reading predicts reading comprehension (i.e., Dixon & Bortolussi, 2013; Feng et al., 2013; McVay & Kane, 2012; Reichle et al., 2010; Sanders et al., 2017; Smallwood et al., 2007, 2008), could be replicated when using frontal TBR as an indicator of state attentional control instead of self-report measures.

Frontal TBR as Indicator for Attentional Control During Reading

In order to fulfil the first aim of the study, expanding previous research on frontal TBR and attentional control to the field of reading, we tested the following four hypotheses:

Hypothesis 1. *The average frontal TBR during reading (as indicator of state attentional control) is related to frontal TBR during a baseline period and a self-report measure of attentional control in daily life.*

In line with previous studies showing strong correlations between scores on trait and state measures of the same ability or characteristic, for example in the case of mindfulness, anxiety and self-esteem, we expected a positive relation between the average frontal TBR during reading, which might be an indicator of state attentional control, and the self-report measure of attentional control in daily life, which reflects trait attentional control (Alessandri et al., 2016; Bertrams et al., 2010; Tsafou et al., 2017). Because frontal TBR during reading might be related to attentional control in daily life (see Angelidis et al., 2016; Putman et al., 2010, 2014), we also expected to find a relation between frontal TBR during reading and during the baseline.

Hypothesis 2. *Frontal TBR during reading differs across text conditions.*

The texts in the current study were read in two conditions that differed in difficulty level (i.e., with and without nonsense words). Research on mind wandering has shown that the frequency of self-reported mind wandering, or lapses in attentional control, increases with text difficulty (Feng et al., 2013; Forrin et al., 2017; Soemer & Schiefele, 2019). In line with this reasoning, we expected lower average attentional control during reading, in the text condition with nonsense words compared to the text condition without nonsense words which might be indicated by the average frontal TBR during reading to be higher.

Hypothesis 3. *Fluctuations in frontal TBR during reading are related to higher frequencies of self-reported mind wandering.*

In line with McVay and Kane's (2010) *control failure x concerns* theory of mind wandering, we expected that the frequency of self-reported mind wandering (reflecting lapses in attentional control) might be related to fluctuations in frontal TBR during reading. Another possibility, however, is that frequencies of self-reported mind wandering and fluctuations in frontal TBR are only weakly correlated because the sensitivity of self-report measures may suffer from the fact that the natural reading process is hindered and that unconscious lapses in attentional control cannot be self-reported (Seli et al., 2016).

Hypothesis 4. *The degree of fluctuations on frontal TBR during reading (i.e., SD in frontal TBR among text pages) is related to frontal TBR during the baseline.*

In line with research on sustained attention, in which fluctuations in reaction times to stimuli are used as indicators of attentional stability (for a review see Fortenbauch et al., 2017), we expected that students who are better at regulating their attention as might be indicated by lower baseline frontal TBR (as indicated by lower average scores) show more stable levels of frontal TBR (as indicated by smaller *SDs*) during reading .

Attentional Control as Predictor of Reading Comprehension

In order to fulfil the second aim of the study, replicating previous research showing that attentional control during reading predicts reading comprehension and provided that frontal TBR is related to attentional control, two hypotheses were tested:

Hypothesis 5. *The average frontal TBR during reading and/or fluctuations in frontal TBR during reading predict reading comprehension of the text.*

In line with the literature on attention and reading comprehension (Dixon & Bortolussi, 2013; Feng et al., 2013; McVay & Kane, 2012; Reichle et al., 2010; Sanders et al., 2017; Smallwood et al., 2007, 2008) we expected a negative relation between the average frontal TBR or fluctuations in frontal TBR during reading and reading comprehension, indicating that better attentional control is related to better reading comprehension. If so, this would support the predictive validity of frontal TBR as a state measure of attentional control. Additionally, previous research on mind wandering and reading comprehension showed that mind wandering is not only reported more often but also particularly detrimental for reading comprehension in the case of difficult texts (Feng et al., 2013; Forrin et al., 2017; Smallwood & Schooler, 2006; Soemer & Schiefele, 2019). In line herewith, relations between frontal TBR or fluctuations on frontal TBR during reading and reading comprehension might be stronger for the text with nonsense words, i.e., the more difficult text.

Hypothesis 6. *The relation between the participants' frontal TBR during the baseline period and reading comprehension could be mediated by the relation between participants' (1) frontal TBR during reading or (2) fluctuations in frontal TBR during reading (i.e., possible indicators of state attentional control) and reading comprehension.*

As George (1991) argued, the added value of a state measure compared to a trait measure is the higher sensitivity to meaningful fluctuations influenced by situational circumstances or interactions between the person and the specific situation or activity (i.e., reading a text that is more or less difficult). In the case of frontal TBR as an indicator of attentional control, we expected that frontal TBR during the baseline period is related to frontal TBR or fluctuations in frontal TBR during reading, but that the relation between frontal TBR during the baseline period and reading comprehension is only indirect, through an effect of frontal TBR or fluctuations in frontal TBR during reading on reading comprehension. A similar mediation effect was recently found for trait mindfulness, state mindfulness and physical activity (Tsafou et al., 2017).

Materials and Methods

Participants

Participants were 28 healthy first-year female students in Social Sciences from a Dutch university, who voluntarily signed up for participation. Participants were between 18 and 29 years old (*M* = 19.29, *SD* = 2.24). Because of the large proportion of female students within the faculty, it was decided to include only female participants. Participants could only participate if they were right-handed native Dutch speakers without learning disabilities and had good or corrected vision. Participants were not permitted to use drugs or medication (with the exception of contraceptives) two weeks prior to the experiment. Students were recruited through advertisement on the university website and signed an informed consent prior to participating. Students received research participation credits that they could use for their study. During the experiment four students reported that they were familiar with the novel from which the texts in the study were derived. These students were excluded resulting in a final sample of 24 students (*M* = 19.29 years, *SD* = 2.24).

Research Design

A within-subjects experimental design with two text conditions differing in difficulty was executed: (1) text with nonsense words versus (2) text without nonsense words. Two comparable texts (A and B) were used in each condition, resulting in four possible combinations of text order (A and B) and conditions (with or without nonsense words), which were randomly assigned to each participant. The combination of a within-subjects design and the random assignment of text order and condition to each participant prevents possible biases, as a consequence of text order, fatigue or differences between the text A and B, to influence the results of the study.

Procedure

The procedures in the present study were approved by the ethics committee of the department of Education and Child Studies.

First Session

The first session, lasting approximately one and a half hour, took place in the EEG-lab at the university. An EEG sensor net was first placed on the head of the participant. Subsequently, two three-minutes baseline measures were recorded: one with the eyes closed and one with the eyes open. Next, the concept *mind wandering* was explained to the participant. In line with the definition of mind wandering used in previous research (for a review see Smallwood & Schooler, 2015), the following instruction was provided: "Mind wandering is used to indicate what happens if your attention is distracted from a task. You may be thinking of personal things or worries instead of reading the text. In other cases you become distracted because you are tired or bored. You are not consciously thinking about something else; you only know that you are not focused on the content of the text. Everyone mind wanders sometimes, especially during longer tasks as reading a text." After the explanation, participants read one of the two texts either with or without nonsense words. Texts were presented on a computer screen. In order to assess attentional control during reading, at eight fixed points in the text, randomly chosen by the researcher (after every 2-5 pages), a question appeared on the screen asking whether the participant was mind wandering or not. After the student finished reading the text, reading comprehension was measured using a recall task in which the participants had to write a one-page summary of the text they read. After a five-minute break in which the signal of the electrodes in the EEG-net was checked, the same procedure was followed with the second text.

Second Session

A second session, taking place in a quiet laboratory room at the university, was planned within two weeks after the first one. Participants completed the Attentional Control Scale and the BRIEF-A, measuring attentional control in daily life.

Materials

The target texts were two passages of respectively 2,524 and 2,545 words from a Dutch translation of the novel "A Clockwork Orange" (Burgess, 1962/2012). The passages were taken from two separate chapters and were understandable without knowing the rest of the storyline. Events in the two chapters did not necessarily have to take place in the order they appeared in the book, which made counterbalancing of the order of the two texts possible. Although the book contains multiple highly violent passages, the texts used in the present study did not include excerpts of these violent passages. The original texts included nonsense words from a fictional language, referred to as Nadsat, that was used by some of the characters in the book (e.g., 'wesjes' for *things* and 'kopatten' for *understanding*; for a dictionary of the English version of the Nadsat language used in the book, see www.nadsatdictionary.com). Text A included 122 nonsense words (4.8% of the total number of words), text B included 136 nonsense words (5.3% of the total number of words). Two conditions were created for each of the two passages, a difficult condition that included the nonsense words and an easier condition in which the nonsense words were replaced by their regular Dutch meaning. The texts were presented on a computer screen in paragraphs of approximately 100 words. Participants could only move forward in the text.

Measurement Instruments

Two self-report measures were used to assess attentional control in daily life: (1) Attentional Control Scale (Derryberry & Reed, 2002), and (2) BRIEF-A (Scholte & Noens, 2011).

Attentional Control Scale (ACS)

Participants rated twenty statements about attention and concentration in daily life on a four-point Likert-scale (e.g., 'It's very hard for me to concentrate on a difficult task when there are noises around' and 'After being disrupted or distracted, it is easy for me to shift my attention away from the distractor'). Sum scores on the two subscales of the ASC, focused attention and attentional shifting, were calculated. The subscale focused attention consisted of nine items, with a sum score ranging from 9 to 36 points. Internal consistency was Cronbach's $\alpha = .61$. The subscale attentional shifting consisted of eleven items, with a sum score ranging from 11 to 44 points. Internal consistency was Cronbach's $\alpha = .62$.

BRIEF-A

Participants rated the frequency of behaviours and thoughts on a 3-point Likert-scale. The self-report questionnaire consisted of 75 items on executive functioning in daily life. In the present study we used the Cognitive Flexibility subscale of the BRIEF-A because this subscale measures attentional shifting among tasks and thoughts. The subscale consisted of 6 items (e.g., 'I have trouble making the transition from one task or activity to another', or' I get upset from sudden changes in my daily routines'). A total score was calculated for each participant, ranging from 6 to 18 points, with a higher score reflecting better attentional shifting. Internal consistency of the scale was Cronbach's $\alpha = .58$, which was regarded acceptable considering the low number of items (Field, 2013).

Aggregate Score for Attentional Control in Daily Life

In order to reduce the number of variables and to prevent that multicollinearity among the self-reports may cause problems in further analyses, the subscales focused attention and attentional shifting (ACS) and cognitive flexibility (BRIEF-A) were combined into one aggregate measure for attentional control in daily life. Principal component analysis applied to the three subscales resulted in one component, containing component loadings ranging from .73 to .89, explaining 67.8% of the variance. Scores were combined by calculating the average standardized score, with a higher score reflecting better attentional control.

Frontal TBR

EEG data were recorded during a baseline period and during reading. We used 129-channel hydrocel Geodesic sensor nets and electrodes were placed according to the 10-20 system amplified by a NetAmps300 amplifier at a digitization rate of 500Hz (Electrical Geodesics Inc.). Impedances were kept below 50 kΩ. Raw data were further processed offline using Brain Vision Analyzer 2.0 software (Brain Products). Data were low-pass filtered at 100 Hz (-3 dB, 48 dB/oct) and high-pass filtered at 0.3 Hz (99.9% pass-band gain, 0.1% stop-band gain, 1.5 Hz roll-off) with a notch-filter of 50 Hz to eliminate electrical noise. Subsequently, EEG data were referenced to the average activity in all channels and ocular correction was performed using the Gratton and Coles' procedure (Gratton et al., 1983). To retain as much artefact-free data as possible, raw EEG data were segmented in 2-second segments with an overlap of 5%. Segments containing artefacts (defined as: voltage steps exceeding 50 µV/ms, differences in values above 100 µV within an interval of 200 ms, amplitudes lower than -70 µV or higher than 70 µV or segments containing less than 0.5 μV activity in intervals of 100 ms intervals) were excluded from further analyses. In addition, noisy channels were replaced by average activity of the closest electrodes. After segmenting the data and correcting for artefacts, power densities in the theta (4-7 Hz) and beta (13-30 Hz) frequency bands were calculated with a fast Fourier transformation (resolution 0.25 Hz, hamming window 10%). Frontal TBR was calculated for the two three-minutes baseline periods and for each text page, based on the average power density of three frontal electrodes (F3, Fz and F4, represented by electrode numbers 24, 11, and 124 respectively; Putman et al., 2010, 2014). Because of non-normality, power density values within each frequency band were log-normalized before calculating the ratios. The average frontal TBR during the baseline was calculated by averaging frontal TBR for both baseline periods (i.e., eyes closed and eyes open). The average frontal TBR during reading was calculated by averaging frontal TBR for all text pages within each text condition (with and without nonsense words). Higher ratios reflected lower attentional control. Additionally, the standard deviation of frontal TBR among all text pages was also calculated for both text conditions, indicating the level of fluctuations in frontal TBR during reading.

Self-Reported Mind Wandering

Reading passages were interrupted at eight random points with the question: “Were you mind wandering?”. This probe appeared only at moments when participants pressed the button to go to the next page. Participants could answer the mind wandering question by indicating ‘yes’ or ‘no’. The probes were presented within intervals of 2-5 pages (i.e., after 200-500 words). The frequency of self-reported mind wandering was used as an indicator of lapses in attentional control during reading.

Reading Comprehension

The one-page summaries participants wrote were coded based on a list of 12 main elements from text A and 15 elements from text B, constructed by the researchers, including the main characters (e.g., Alex is a boy who does a lot of things which are illegal), events in the text (e.g., Alex has a nightmare about violence), motives of characters (e.g., Alex will be obedient during his treatment because he hopes that he then will be liberated soon), and relations between events (e.g., Alex got a visit from his probation officer, because the officer had heard rumours about a fight in which Alex’ name appeared). A percentage of correctly mentioned main elements for each summary was calculated. Two coders independently coded all summaries. Intercoder-reliability for all separate main elements in the summaries equalled *r* = .93 (intraclass correlation). Final scores were based on consensus after discussing disagreements.

Statistical Analyses and Data Reduction

Data on all outcome measures were complete for all participants (*N* = 24), except for the ACS (*n* = 22) which was not filled in by two participants. As a consequence, no aggregate scores for attentional control in daily life were available for these two participants. The variable *SD* in frontal TBR, which was calculated as an indicator of the amount of fluctuations in frontal TBR among the pages in each text condition (with and without nonsense words), included three outliers (*z*-score > 3) in the text condition with nonsense words. These scores were winsorized into .001 higher than the highest non-outlying value (Hampel et al., 1986). The rank order of scores was maintained by adding .001 to each next outlier. For *SD* in frontal TBR in the text condition without nonsense words, two outliers were winsorized.

Differences in scores between the two text conditions (with and without nonsense words) were tested using paired *t*-tests. In order to assess the strength and direction of an association between two variables we executed Pearson's product-moment correlations. Only reporting the *p*-value for an analysis is not adequate to fully understand the results as this value is not only dependent on the effect size but also on the sample size. Therefore, next to the significance level of the test statistics, we reported the effect sizes and the 95% confidence intervals of the effect sizes for all (paired) *t*-tests and correlational analyses (see Lancaster et al., 2002; Maxwell, 2004). Additionally, we decided to interpret alpha levels between .05 and .10 as marginally significant (see Gail et al., 2012; Noymer, 2011). Effect sizes for marginally significant and significant differences and correlations were interpreted based on Cohen's criteria (Cohen, 1992).

To test if the average frontal TBR or fluctuations in frontal TBR during reading would mediate the relation between the average frontal TBR during the baseline and reading comprehension, we performed mediation analyses following the steps proposed by Baron and Kenny (1986) and tested the significance of the mediation using Sobel's test.

Results

Descriptive Statistics

Participants tended to spend more time reading the text with nonsense words than the text without nonsense words (*t* (23) = -1.77, *p* = .09, *d* = 0.25, 95% CI = [-0.32, 0.82], paired *t*-test). Furthermore, participants reported mind wandering marginally significantly more often when reading the text with nonsense words than without nonsense words (*t* (23)= -1.95, *p* = .06, *d* = 0.39, 95% CI = [-0.18, 0.96], paired *t*-test), and recalled a marginally significantly greater number of main elements of the text without nonsense words than the text with nonsense words (*t* (23)= 2.07, *p* = .05, *d* = 0.54, 95% CI = [-0.04, 1.11], paired *t*-test). Descriptive statistics for the behavioural outcome measures in both text conditions are reported in Table 1. Although differences were marginally significant, taken together, the pattern of results for reading time, mind-wandering, and recall support the idea that the text with nonsense words was more difficult for participants to process than the text without nonsense words.

Frontal TBR During Reading, During the Baseline, and Attentional Control in Daily Life

Frontal TBR During Reading and During the Baseline

In line with what we expected according to hypothesis 1, the average frontal TBR during reading correlated strongly with frontal TBR during the baseline (*M* = 0.41, *SD* = 0.22). This was the case in both the text condition with nonsense words (*M* = 0.29, *SD* = 0.39, *r* = .69, *p* < .001, 95% CI = [.40, .85]) and the text condition without nonsense words (*M* = .0.26, *SD* = 0.29, *r* = .52, *p* < .001, 95% CI = [.15, .76], see Table 2).

Frontal TBR During Reading and Self-Reported Attentional Control in Daily Life

The average frontal TBR during reading in the text condition with nonsense words was marginally significantly related to self-reported attentional control in daily life (*r* = -.41, *p* = .06, 95% CI = [-.70, -.01]). Participants who reported to be better able to control their attention during daily life, had on average a lower average frontal TBR during reading, reflecting better attentional control during reading. However, the first hypothesis is only partly confirmed at this point. That is, the relation between frontal TBR during reading in the text condition without nonsense words and self-reported attentional control in daily life was not significant (*r* = -.26, *p* = .24, 95% CI = [-0.60, 0.16]).

Differences in Frontal TBR During Reading Between Text Conditions

Contrary to what was expected according to hypothesis 2, no difference was found between the average frontal TBR during reading in the text condition with nonsense words (*M* = 0.29, *SD* = 0.39) and the average frontal TBR during reading in the text without nonsense words (*M* = 0.26, *SD* = 0.29, $t(23) = 0.36$, $p = .72$, $d = -0.20$, 95% CI = [-0.77, 0.36]).

Fluctuations in Frontal TBR During Reading and Self-Reported Mind Wandering

In line with hypothesis 3, both in the text condition with nonsense words ($r = .37$, $p = .07$, 95% CI = [-.04, .67]) and the text condition without nonsense words ($r = .34$, $p = .10$, 95% CI = [-.07, .65]), standard deviations in frontal TBR among pages within a text were marginally significantly correlated with the self-reported frequency of mind wandering. In other words, students who showed a higher level of fluctuations in TBR among pages within a text tended to also report mind wandering more often during the text.

Fluctuations in Frontal TBR During Reading and Frontal TBR During the Baseline

Hypothesis 4 was confirmed for the text with nonsense words but not for the text without nonsense words. For the text condition with nonsense words, the relation between the average frontal TBR during the baseline and the standard deviation in frontal TBR among text pages was significant and strong ($r = -.52$, $p = .01$, 95% CI = [-.76, -.15], see Table 2). Students with lower average frontal TBR during the baseline showed more fluctuations in frontal TBR during reading. For the text condition without nonsense words, we found a similar pattern, however this relation was less strong and only marginally significant ($r = -.37$, $p = .08$, 95% CI = [-.67, .04]).

Frontal TBR During Reading or Fluctuations in Frontal TBR as Predictor for Reading Comprehension

For the text condition with nonsense words, a significant relation was found between the *average* frontal TBR during reading and reading comprehension ($r = -.56$, $p < .01$, 95% CI = [-.79, -.20]), a large effect (Cohen, 1992). A lower frontal TBR that might indicate better attentional control during reading, was related to a higher number of main elements recalled from the text after reading. This result is in line with hypothesis 5. Students who are on average better in controlling their attention during reading will score higher on reading comprehension. However, the fifth hypothesis was not completely confirmed as fluctuations in attentional control during reading were not related to reading comprehension of the text (r = .08, p = .71, 95% CI = [-.33, .47]). In the same vein, for the text condition without nonsense words, neither the *average* frontal TBR (r = -.04, p = .84, 95% CI = [-.44, .37]), nor the level of *fluctuations* in frontal TBR during reading (r = .07, p = .74, 95% CI = [-.34, .46]) were related to reading comprehension.

Frontal TBR During the Baseline, During Reading and Reading Comprehension

In line with hypothesis 6, for the text with nonsense words, mediation analysis showed a significant indirect effect of the average frontal TBR during the baseline on reading comprehension through the average frontal TBR during reading (see Figure 1; R^2 = .31, F(2, 21) = 4.82, p = .02, tolerance = .53, VIF = 1.90). In other words, attentional control during reading, for which the average frontal TBR during reading might be indicative, significantly mediated the relationship between the average frontal TBR during the baseline and reading comprehension (Sobel test = -1.97, SE = 13.46, p = .05). Because fluctuations in frontal TBR during reading were related to reading comprehension in neither of the text conditions, and the average frontal TBR was not related to reading comprehension in the text condition without nonsense words, no mediation analyses were performed for these variables.

Discussion

The first aim of the present study (see hypotheses 1 to 4) was to clarify the value of frontal TBR as a state measure of attentional control during reading. To explore the validity of frontal TBR as a state measure of attentional control, we related the average frontal TBR during reading to the average frontal TBR during the baseline and to attentional control in daily life as measured by self-report questionnaires. Frontal TBR during reading and during the baseline were strongly related. Frontal TBR during reading was marginally significantly and moderately related to attentional control in daily life, but frontal TBR during the baseline and during reading in the text condition without nonsense words were not related to attentional control in daily life. The strength of the correlation between frontal TBR in the text condition with nonsense words and attentional control in daily life was comparable to relations found in previous studies in which frontal TBR was measured during resting conditions and tested in relation to attentional control (Angelidis et al., 2016; Putman et al., 2010, 2014). No difference was found between the average frontal TBRs in the text conditions with and without nonsense words.

Participants who showed higher levels of fluctuations in frontal TBR during reading tended to report mind wandering more often. These relations were marginally significant with a moderate effect size in both text conditions. The relations between fluctuations in frontal TBR and mind wandering found in the current study are in line with results in the literature where differences in frontal TBR between periods of mind wandering and periods of on task behaviour using a cognitively less complex task were found (Braboszcz & Delorme, 2011; van Son et al., 2019a). Additionally, the relations between fluctuations in frontal TBR and the self-reported frequency of mind wandering support the *control failure x concerns* theory of mind wandering (McVay & Kane, 2010), stating that mind wandering is a consequence of a failure of the attentional control system to suppress task-irrelevant thoughts and feelings. If periods of mind wandering do not represent a failure of the attentional control system, but a redirection of attentional control which appeals to the same resources (see Smallwood & Schooler, 2006), one would expect the attentional control system to be equally active during reading as during mind wandering. Accordingly, no fluctuations in frontal TBR would be expected.

We also investigated the relations between frontal TBR during the baseline and the level of fluctuations in frontal TBR during reading. Contrary to what we expected (see hypothesis 4), lower levels of frontal TBR during the baseline, which were related to lower attentional control in previous studies (e.g., Aldemir et al., 2017; Angelidis et al., 2016; Putman et al., 2010, 2014; van Son et al., 2018), were related to a higher level of fluctuations in frontal TBR during reading. However, research has shown that people who show high levels of attentional control are also better in controlling mind wandering in accordance with the cognitive demands of the task (Golchert et al., 2017; Rummel & Boywitt, 2014). As a consequence, people who can better regulate their attention show less spontaneous or unconscious mind wandering, but report more often to deliberately mind wander during a task (Golchert et al., 2017). Therefore an alternative interpretation might be that fluctuations in frontal TBR may also represent the ability of a reader to maintain the balance between periods of fully focusing on the text and moments of mind wandering. That is, these participants might be better able to consciously controlling their attention, and, are able to bring their focus back on the text when necessary, for instance when reading parts of the text were information density is high or for sections that are more complex or where the presented information is central for understanding the text.

The second aim of the present study (see hypothesis 5 and 6) was to explore whether the relation between attentional control and reading comprehension found in previous studies (Dixon & Bortolussi, 2013; Feng et al., 2013; McVay & Kane, 2012; Reichle et al., 2010; Sanders et al., 2017; Smallwood et al., 2007, 2008), could be replicated when using frontal TBR during reading as a biomarker for state attentional control. A strong relation was found between frontal TBR during reading and reading comprehension for the text condition with nonsense words, but not for the text condition without nonsense words. Also, self-reported mind wandering was not related to reading comprehension. The discrepancy among the relation between frontal TBR during reading and reading comprehension found in the text condition with nonsense words but not in the text condition without nonsense words is in line with previous findings showing that failures in attentional control are particularly detrimental for comprehension of difficult texts (Feng et al., 2013). In other words, as expected, attentional control seems especially important for deep reading to understand complex texts (LaRusso et al., 2016). Additionally, we found that frontal TBR during reading (as indicator of state attentional control) fully mediated the relation between frontal TBR during the baseline and reading comprehension. Multicollinearity was not a problem in this mediation analysis (i.e., correlations between the predictors were below .80 and VIF was far below 5; see Craney & Surles, 2002; Pedhazur 1997), supporting the idea that state attentional control during reading can be measured separately from baseline attentional control using frontal TBR as a biophysiological marker. The mediation model shows us that attentional control in general is important, but that it only partially explains attentional control under specific circumstances, in the case of our study during reading a difficult text, and that especially attentional control during reading is an important predictor of reading comprehension. This emphasizes the importance of being able to monitor attentional control during reading in an ecologically valid way using a measure that is sensitive for fluctuations in attentional control without disturbing the reading process.

Despite the preliminary nature of the data and the low power, the results of the present study and the strong effect sizes in particular (up to $r = 0.69$; Cohen, 1992), do suggest that frontal TBR has potential as biophysiological marker for attentional control during reading. The advantage of EEG, compared to self-reports of mind wandering as indicator of lapses in attentional control, is that it measures brain potentials without interrupting the natural reading process. The fact that the presentation of text is not restricted to single words or sentences enhances ecological validity of the measurement instrument. Additionally, individual differences in frontal TBR during reading were related to self-reported attentional control in daily life and to reading outcomes in the text condition with nonsense words. Higher ratios, indicating less attentional control, were related to less attentional control in daily life and lower reading comprehension. The fact that relations between attentional control in daily life, attentional control during reading and reading comprehension were mainly present in the text condition with nonsense words is consistent with literature showing that attentional control is particularly important in executing complex tasks (Feng, et al., 2013; Golchert et al., 2017; Larusso et al., 2016). Besides that, frontal TBR seemed to be sensitive for fluctuations in attentional control, as appeared from the moderately strong, although marginally significantly, relations between fluctuations in frontal TBR and the self-reported frequency of mind wandering (i.e., lapses in attentional control). This might indicate that fluctuations in frontal TBR during reading reflect meaningful differences in attentional control (i.e., lapses in attentional control), which advocates for the suitability of frontal TBR as an indicator for state attentional control.

Limitations and Future Research

The present study is an exploratory study with a small sample resulting in low statistical power. Therefore, although the present study contains promising results and effect sizes, the present study should be replicated with larger and more diverse samples (e.g., boys, girls, readers with and without reading difficulties) to affirm the results. Considering the close relationship between executive functions like attentional control and intelligence (Jurado & Rosselli, 2007), future research should investigate frontal TBR during reading as a measure for attentional control during reading with other samples. Additionally, the texts used in this study were relatively short compared to texts used in previous studies on mind wandering (e.g., Dixon & Bortolussi, 2013; Feng et al., 2013; McVay & Kane, 2012; Reichle et al., 2010; Smallwood et al., 2008). Future research should also focus on the course of attentional control during reading longer texts and its influence on reading outcomes. Additionally, future research could focus on possible differences in brain activity underlying deliberate and spontaneous moments of mind wandering, to gain more insight in the relation between mind wandering and attentional control (see Golchert et al., 2017). In the present study, we were not able to distinguish between spontaneous and deliberate mind wandering. A promising approach to gain more insight in processes underlying lapses in attentional control is the combination of eye movements data (e.g., pupil size; Konishi et al., 2017; fixation duration; Reichle et al., 2010; within-word regressions; Uzzaman & Joordens, 2011; eye blinks; Smilek et al., 2010, see also Faber et al., 2018; Schad et al., 2012) and EEG-recordings. Both techniques are becoming more and more accessible due to the rapid technological innovations and methods for co-registration of eye-movements and EEG are becoming increasingly popular in studying cognitive processes in naturalistic settings (Nikolaev et al., 2016). Both methods can be used to further unravel the processes underlying attentional control without hindering the natural reading process (see also Dimigen et al., 2011).

Insight into the course of attentional control during reading could be a starting point for developing interventions and instruction methods that guide task-related attentional processes. For example, Sanders et al. (2017) found that explicitly instructing people to monitor their attention (i.e., being focused on detecting moments of mind wandering and refocus when mind wandering occurs) during reading resulted in less mind wandering, but this method had a negative effect on comprehension. Alternatively, instructing participants to focus on constructing a mental model during reading did not result in less mind wandering – as was indicated by the self-reported frequency of mind wandering – but did improve reading comprehension (Sanders et al., 2017). Encouraging results have been found in a study using a brain-computer interface to help readers control their attention during reading, demonstrating the usefulness of single-electrode EEG devices to monitor attention during reading and to remind the reader to stay focused when attention is fading (Chen & Huang, 2014).

Conclusion

The present study is, to the best of our knowledge, the first one in which attentional control during reading was assessed using frontal TBR. Results suggest that frontal TBR is a promising biophysiological marker for attentional control during reading as: (1) frontal TBR during reading a complex text was marginally significantly related to self-reports of attentional control in daily life, (2) frontal TBR during reading was strongly related to baseline frontal TBR, (3) fluctuations in frontal TBR were related to the frequency of self-reported mind wandering and to baseline frontal TBR, (4) frontal TBR during reading significantly predicted reading comprehension in a complex text, and (5) frontal TBR during reading mediated the relationship between baseline frontal TBR and reading comprehension in the complex text. Given the low power but promising effect sizes found in the present research, particularly in the complex text condition, replication of results with larger and more diverse samples and with different texts is needed before firm conclusions can be drawn.

Table 1

Descriptive Statistics for the Behavioural Outcome Measures in Both Text Conditions

		With nonsense words				Without nonsense words			
	N	Min.	Max.	*M*	*SD*	Min.	Max.	*M*	*SD*
Mind wandering (max. 8)[1]	24	0.00	7.00	3.71	2.01	0.00	6.00	3.00	1.62
Reading time (minutes)	24	6.28	15.62	10.64	2.58	7.35	15.35	10.05	2.14
Recall task (% correct)	24	0.00	60.00	25.56	15.69	13.30	53.30	32.78	10.93

Note. [1]The number of times participants reported to be mind wandering (i.e., responded 'yes' on the mind wandering questions).

Table 2

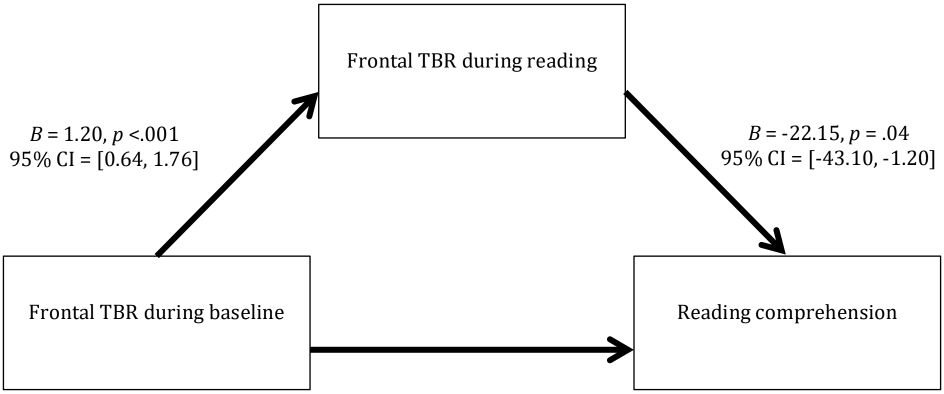
Correlations Among Frontal TBR and Other Outcome Measures

		Condition with nonsense words					Condition without nonsense words				
		1.	2.	3.	4.	5.	1.	2.	3.	4.	5.
1.	Attentional control in daily life (factor score)	1					1				
2.	Frontal TBR during baseline[1]	-.35	1				-.35	1			
3.	Frontal TBR during reading[1]	-.41†	.69**	1			-.26	.52**	1		
4.	*SD* frontal TBR during reading	.34	-.52**	-.43*	1		.22	-.37†	-.75**	1	
5.	Self-reported mind wandering	-.32	-.26	-.08	.37†	1	-.12	-.36†	-.31	.34†	1
6.	Reading comprehension	.38	-.40†	-.56**	.08	-.16	.47*	-.22	-.04	.07	-.31

Note: [1]higher ratios represent lower levels of attentional control. † p <.10; * p <.05; ** p <.01

Figure 1:

Diagram Showing the Mediation Effect of Students' Attentional Control During Reading, as Might be Indicated by the Average Frontal TBR During Reading, for the Relation Between Average Frontal TBR During the Baseline and Reading Comprehension in the Text Condition With Nonsense Words.



Direct effect: B = -27.80, p = .06, 95% CI = [-56.33, 0.73]

Indirect effect: B = -1.27, p = .94, 95% CI = [-37.70, 35.16]