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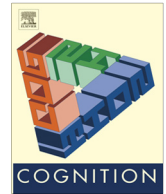
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Your mind wanders weakly, your mind wanders deeply: Objective measures reveal mindless reading at different levels

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ABSTRACT

When the mind wanders, attention turns away from the external environment and cognitive processing is decoupled from perceptual information. Mind wandering is usually treated as a dichotomy (dichotomy-hypothesis), and is often measured using self-reports. Here, we propose the levels of inattention hypothesis, which postulates attentional decoupling to graded degrees at different hierarchical levels of cognitive processing. To measure graded levels of attentional decoupling during reading we introduce the sustained attention to stimulus task (SAST), which is based on psychophysics of error detection. Under experimental conditions likely to induce mind wandering, we found that subjects were less likely to notice errors that required high-level processing for their detection as opposed to errors that only required low-level processing. Eye tracking revealed that before errors were overlooked influences of high- and low-level linguistic variables on eye fixations were reduced in a graded fashion, indicating episodes of mindless reading at weak and deep levels. Individual fixation durations predicted overlooking of lexical errors 5 s before they occurred. Our findings support the levels of inattention hypothesis and suggest that different levels of mindless reading can be measured behaviorally in the SAST. Using eye tracking to detect mind wandering online represents a promising approach for the development of new techniques to study mind wandering and to ameliorate its negative consequences.

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1. Introduction

Most people experience mental states in which they are no longer attending to the task at hand and are instead thinking about something else (Schooler et al., 2011; Smallwood & Schooler, 2006). This ubiquitous phenomenon of mind wandering, which was long ignored in the cognitive sciences, has recently received considerable attention (Christoff, Gordon, Smallwood, Smith, & Schooler, 2009; Killingsworth & Gilbert, 2010; Levinson, Smallwood,

& Davidson, 2012; McVay & Kane, 2010; Reichle, Reineberg, & Schooler, 2010) and is thought to be tightly related to the brain's default mode of operation (Buckner, Andrews-Hanna, & Schacter, 2008; Mason et al., 2007). Mind wandering and task focus are typically treated as a dichotomy (Schooler et al., 2011; Smallwood, 2010b; Smallwood et al., 2011), where people are either mind wandering or focused on a given task. To investigate dichotomous aspects of mind wandering many previous studies have relied on subjective self-reports (Giambra, 1995; Smallwood & Schooler, 2006). Our main goal with the present work is to propose the levels of inattention hypothesis, which assumes that different hierarchical levels of cognitive processing are decoupled from external input in a graded fashion, reflecting states of deep and weak attentional decoupling. To measure different levels of decoupling during reading, we introduce a new paradigm,

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the sustained attention to stimulus task (SAST), which is based on signal detection analyses of readers' sensitivity for errors in the text. Analyses of a large dataset of eye movements during mindless reading support the levels of inattention hypothesis and show that eye tracking technology can be utilized to predict states of mindless reading online.

The phenomenon of mind wandering involves two specific alterations in cognitive processing (Schooler et al., 2011; Smallwood & Schooler, 2006). First, during mind wandering attention is directed away from the external environment (i.e., attention lapses), which reduces cognitive processing of perceptual information (Kam et al., 2011; Smallwood, Beach, Schooler, & Handy, 2008). This process of attentional (or perceptual) decoupling can lead to failures in the performance of external tasks (Christoff et al., 2009; McVay, Kane, & Kwapil, 2009; Robertson, Manly, Andrade, Baddeley, & Yiend, 1997; Smallwood, Riby, Heim, & Davies, 2006). Second, mind wandering often involves stimulus independent thought (SIT) where attention is directed towards internal information derived from memory (Smallwood & Schooler, 2006; Stawarczyk, Majerus, Maquet, & D'Argembeau, 2011).

The cognitive sciences have described the mind as consisting of a multitude of different cognitive processes (Gazzaniga, 2009). As one important principle these processes are organized at different hierarchical levels, ranging from early low-level perceptual-motor processes towards increasingly abstract representations at higher levels (Cohen, 2000; Craik & Lockhart, 1972; Gazzaniga, 2009). For reading, various models – including models of eye-movement control (Engbert, Nuthmann, Richter, & Kliegl, 2005; Reichle, Warren, & McConnell, 2009) and theories of language processing (Graesser, Olde, & Klettke, 2002; Kintsch, 1998; Malmkjaer, 2002) – have postulated hierarchical processing at visuomotor, lexical, syntactic, semantic, and discourse levels. How (in)attention affects different lower and higher levels of stimulus processing was long discussed in the debate about early (Broadbent, 1958) versus late (Deutsch & Deutsch, 1963; Treisman, 1960) attentional selection, and there is evidence that attentional selection can attenuate processing at early or late stages (Chun, Golomb, & Turk-Browne, 2011; Lavie, 2005).

Mind wandering reduces external attention and can attenuate stimulus processing at all levels of the cognitive hierarchy (for review see Smallwood, 2011). This was demonstrated in studies investigating high-level episodic memory encoding (Riby, Smallwood, & Gunn, 2008; Smallwood, Baracaia, Lowe, & Obonsawin, 2003; Smallwood, McSpadden, & Schooler, 2008; Smallwood et al., 2006), intermediate task-relevant stimulus processing (Barron, Riby, Greer, & Smallwood, 2011; O'Connell et al., 2009; Smallwood et al., 2008), early low-level multimodal perceptual processing (Kam et al., 2011; Weissman, Roberts, Visscher, & Woldorff, 2006), and sensory input processes (Smilek, Carriere, & Cheyne, 2010b). The present work concerns how these diverse findings can be integrated into a coherent theoretical framework.

The cascade model of inattention (Smallwood, 2011; Smallwood, Fishman, & Schooler, 2007) proposes a mechanism to explain decoupling in a hierarchical cognitive system. According to the model, mind wandering

reduces cognitive processing of incoming information at a very early perceptual level and across multiple sensory modalities. The consequences of such low-level decoupling then “cascade downward through the cognitive system” (Smallwood et al., 2007, p. 233) and cause decoupling at higher levels. Based on this mechanism, the model parsimoniously explains why decoupling impairs performance in “as wide a range of tasks as perception, encoding and reading” (Smallwood, 2011, p. 68).

Stimulus-independent thought and stimulus-dependent thought are usually treated as a dichotomy (Smallwood et al., 2011), and this view has dominated previous research (e.g., Christoff, 2012; Fox et al., 2005; Killingsworth & Gilbert, 2010; Levinson et al., 2012; McVay & Kane, 2012b; Reichle et al., 2010; Smallwood, 2010b). Here, we investigate attentional decoupling and whether it is of a dichotomous or a hierarchically graded nature. First, the dichotomy-hypothesis proposes that different levels of cognitive processing are decoupled from external input in an all-or-none fashion (see Fig. 1a): during task focus all hierarchical levels of cognitive processing are coupled to the external environment, but when the mind wanders this coupling breaks down at all levels. As a potential mechanism, attentional decoupling may always attenuate early perceptual processing stages across modalities (reflecting early attentional selection, Broadbent, 1958) and the consequences of this low-level decoupling may cascade into the system to impair analysis at higher levels (Smallwood, 2011; Smallwood et al., 2007). For the phenomenon of mindless reading, the dichotomy-hypothesis predicts that impaired visual representations of the text prevent a successful analysis at the lexical, syntactic, semantic, and the discourse level.

As an extension of the dichotomous view, we propose the levels of inattention hypothesis (Fig. 1b): We postulate that cognitive processing of external input does not always fail at an early perceptual level, but fails at different hierarchical levels, resulting in different graded degrees of weak and deep attentional decoupling. During occasional episodes of deep decoupling, cognitive processing of external input ceases at an early perceptual level (early attentional selection), and the consequences of this low-level decoupling cascade into the system to cause decoupling at higher levels (Smallwood, 2011; Smallwood et al., 2007). As a new contribution, we postulate states of weak decoupling, where high-level cognitive processing is decoupled from the external environment (i.e., late attentional selection, Deutsch & Deutsch, 1963) but low-level processing is fully intact. Lastly, during states of full attentional coupling external information is processed at all levels. Combining the levels of inattention hypothesis with the cascade model of inattention (Smallwood, 2011; Smallwood et al., 2007) predicts that decoupling at different levels is hierarchical because reduced cognitive processing at one specific level will cause decoupling at higher levels in the hierarchy.

Previous studies on attentional decoupling have typically focused on dichotomous aspects of the decoupling process: many studies investigated decoupling in the sustained attention to response task (SART) via failures to inhibit the response to rare target stimuli (Manly, Robertson, Galloway, & Hawkins, 1999; Robertson et al., 1997;

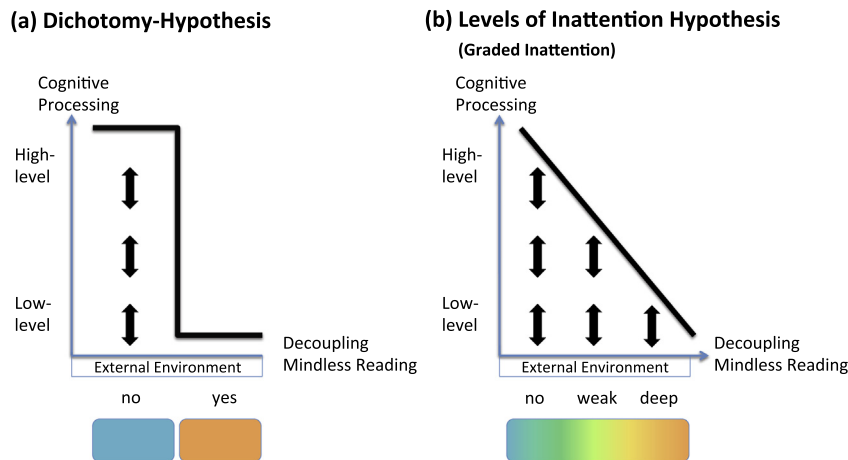


Fig. 1. Schematic illustration of two theoretical hypotheses about how different levels of cognitive processing are decoupled from the external environment during inattention. It is illustrated how high-level and low-level cognitive processing is coupled (below the black line, black arrows) or decoupled (above the black line) from the external environment. (a) The dichotomy-hypothesis proposes that attentional decoupling occurs in an all-or-none fashion, where cognitive processing is either coupled (left, grey) or decoupled (right, black) from external input. (b) The levels of inattention hypothesis proposes graded degrees of decoupling, including fully coupled (left, lightgrey), weakly decoupled (middle, darkgrey), and deeply decoupled (right, black) processing.

Smallwood et al., 2004, 2006), and/or via dichotomous measures of SIT (Kam et al., 2011; Reichle et al., 2010; Smallwood et al., 2008). However, some previous studies suggest that the underlying phenomenon may not be dichotomous. A recent model (Cheyne, Solman, Carriere, & Smilek, 2009) has proposed three discrete states of task engagement/disengagement – occurrent task inattention (to dynamically changing “moment-to-moment stimulus meaning”), generic task inattention (to the “general task environment”), and response disengagement (i.e., inattention to “motor behavior”) – and found support for these states in analyses of the SART (see also Cheyne, Carriere, Solman, & Smilek, 2011; Seli, Cheyne, & Smilek, 2012). Moreover, based on principle component analyses, Smallwood and colleagues (Smallwood, 2010a; Smallwood, McSpadden, Luus, & Schooler, 2008) (also see McVay & Kane, 2012a) showed that performance errors were preceded by a gradual shift in response times from slow to fast responses, which may lend support to a graded nature of decoupling.

With the present work we test theoretical hypotheses by studying attentional decoupling during reading. Mind wandering has long been thought to be elusive to vigorous scientific investigation because it is difficult to induce and control in the laboratory. For example, mindless reading was considered to “be very difficult to study experimentally” (Rayner & Fischer, 1996, p. 746). Previous research has approximated mindless reading via scanning of z-strings, where each letter in a text is replaced by the letter ‘z’ and subjects are asked to move their eyes across the z-strings ‘as if they were reading’ (Nuthmann & Engbert, 2009; Nuthmann, Engbert, & Kliegl, 2007; Rayner & Fischer, 1996; Vitu, O’Regan, Inhoff, & Topolski, 1995). Other studies have approached mindless reading by studying old readers (Wotschack & Kliegl, 2011) or via reading of randomly shuffled text, where the order of words in a text is randomly shuffled and subjects have the task to read the meaningless word lists (Schad & Engbert, 2012;

Schad, Nuthmann, & Engbert, 2010).¹ To catch spontaneous episodes of mind wandering during normal reading, research has focused on thought sampling methods, where subjects are asked to report about their inner experiences of mind wandering (Giambra, 1995; Reichle et al., 2010; Schooler, Reichle, & Halpern, 2004; Smallwood & Schooler, 2006).

Both approaches have their limitations. Approximating mindless reading via paradigms like ‘z’-string scanning may not capture the phenomenon of mind wandering. Studying mind wandering using the thought sampling method is subject to the limitations associated with subjective self-report on cognitive processes, i.e., introspection (Nisbett & Wilson, 1977), and continuously monitoring one’s conscious thought may change behavior. As a complementary approach, indicators for mind wandering have been derived from behavioral measures of attentional decoupling. Previous behavioral approaches include failures to inhibit the response in the sustained attention to response task (SART: Bellgrove, Hawi, Gill, & Robertson, 2006; Christoff et al., 2009; Johnson et al., 2007; Manly et al., 1999; Molenberghs et al., 2009; Robertson et al., 1997; Seli, Cheyne, Barton, & Smilek, 2012; Smallwood et al., 2006; Smilek, Carriere, & Cheyne, 2010a), and reaction times in a word-by-word reading paradigm (Franklin, Smallwood, & Schooler, 2011). However, there is currently a lack of objective measures that catch mind wandering in natural and complex tasks like normal reading.

¹ Based on the levels of inattention hypothesis, we suggest that z-string scanning (Vitu, O’Regan, Inhoff, & Topolski, 1995) may be regarded as approximating a state of deep mindless reading, where no language processing is present. Shuffled text reading (i.e., reading random word lists), to the contrary, may approximate weak mindless reading, where processing of higher-level text meaning is absent, but some processing of individual words is intact (Schad & Engbert, 2012; Schad et al., 2010).

1.1. Present experiment

To fill this gap in current experimental approaches, we introduce the sustained attention to stimulus task (SAST), which is based on psychophysics of error detection in a reading experiment. Our analyses use recordings of eye movements to derive measures for attentional decoupling. Methodologically, we manipulated a corpus of normal text by inserting specific meaningless error sentences containing different kinds of errors. We added a control condition where error sentences contained no error. Readers were asked to indicate whenever they noticed that the text turned meaningless. Mindless reading was operationally defined as (a) overlooking an error passage (single-trial level), and (b) low sensitivity for errors (aggregated level). In this new paradigm, we utilize classical psychophysical methods from signal detection theory (Wickens, 2002) to distinguish between sensitivity for errors (i.e., the propensity for mindless reading) and a general tendency of readers to respond in a certain fashion. The approach does not require instructions about mind wandering, and may be less intrusive and more objective than self-report measures used in previous studies. However, we cannot exclude the possibility that instructions about errors may affect reading behavior as readers may pay increased attention to detect the errors in the text. To counteract such effects we (a) optimized the experimental setting to increase the chance of observing mindless reading in the eye tracker (see Methods section for details) and (b) included high-level errors such that text comprehension was necessary to detect the errors and relatively normal reading can be expected.

To avoid detecting mindlessness when readers were in fact paying attention to the task several measures were taken: first, very easy texts were selected to ensure that readers would have no comprehension difficulties (cf. Smallwood et al., 2007). Second, readers received instructions and examples explaining the different error types.

Third, readers were encouraged to respond also when unsure about the presence of an error.

To generate measures for low-level and high-level decoupling, we constructed errors at different levels of the text (Table 1). (i) We replaced one word in an error sentence by a pseudo-word, causing a *lexical* error. If low-level lexical processing is decoupled from the text, then readers cannot detect lexical errors. Second, (ii) we included *syntactic* errors as a measure for syntactic processing. (iii) Statements that are incompatible with the readers' world knowledge were included to construct *semantic* errors. If medium-level sentence meaning is not processed, then readers cannot detect semantic errors. (iv) We included sentences that clearly contradicted their context to construct *discourse* errors. These can be detected only when readers integrate the meanings from neighboring sentences into a single representation, and thus tested for high-level discourse processing. Lastly (v), we reordered nouns and pronouns from the meaningful control sentences to construct *gibberish text* for comparability with previous research (Smallwood et al., 2007). Readers may automatically construct meaning from meaningless gibberish text without noticing by reordering words (Ferreira, Bailey, & Ferraro, 2002), and we therefore expect gibberish text to reflect high-level construction or repair processes. All errors were constructed to (a) lack an overall meaning and (b) show no similarities to any possible meaningful sentence. For example, pseudo-words were not implemented as spelling-errors, but constructed to have no similarities to any existing word. This was done to ensure that overlooking errors would indicate mind wandering and would not occur because readers constructed meaning from meaningless text.

Based on dichotomous versus graded conceptions of decoupling, we derived predictions for readers' sensitivity for different error types. The levels of inattention hypothesis predicts that sensitivity should differ between error types: readers should be very sensitive to low-level errors (e.g., lexical errors) as these should be overlooked only

Table 1
Types of errors used for error sentences.

Type of error	Construction/description	Example sentence
Control	<ul style="list-style-type: none"> no error, meaningful text 	(1) The wall was made from big worked stones (2) On all birthdays, he congratulates his classmates and the teacher
Lexical	<ul style="list-style-type: none"> one word is replaced by a morphologically & phonologically legal pseudo-word detectable via lexical, but not via pure orthographic or phonological processing does NOT resemble any real word that could fit into the text 	(1) The wall was begrothed from big worked stones
Syntactic	<ul style="list-style-type: none"> one word in the sentence is moved to a different location, causing a syntactic error 	(1) The wall worked was made from big stones
Semantic	<ul style="list-style-type: none"> statements in the sentence contradict world knowledge 	(2) He always thinks of buying new hamsters for the bathroom at school
Discourse	<ul style="list-style-type: none"> neighboring sentences are inconsistent with each other (e.g., direct contradictions of statements) each single sentence is correct (no lexical, syntactic, or semantic error) 	(2) <u>He welcomes the guests</u> on behalf of the class. He congratulates his classmates on their birthdays <u>but never welcomes the guests</u>
Gibberish text	<ul style="list-style-type: none"> changed order of nouns or pronouns within a sentence correct syntax Smallwood et al. (2007) 	(2) On all classmates, he congratulates his birthdays and the teacher

during deep decoupling. To the contrary, readers should be less sensitive to errors assessing high-level text processing (discourse errors, gibberish text) because already weak decoupling prevents detection of these errors. Based on the dichotomy-hypothesis, attentional decoupling should either cause no differences in sensitivity between error types, or any differences in sensitivity should be due to different durations (rather than depths) of mind wandering.

We recorded eye movements in the SAST to derive measures for different levels of cognitive text processing during reading (Rayner, 1998, 2009). Readers usually look longer at phrase- and sentence-final words compared to non-final words, and this wrap-up effect is related to the high-level process of integrating words and constructing a text meaning (Just & Carpenter, 1980; Warren, White, & Reichle, 2009). Moreover, readers look longer at low-frequency words compared to high-frequency words (Inhoff & Rayner, 1986; Just & Carpenter, 1980; Rayner, 1998; Rayner & Duffy, 1986) reflecting low-level lexical processing. Reichle et al. (2010) were the first to study mind wandering during reading using eye tracking. They argued that lexical and linguistic influences on eye movements are reduced during mindless reading, indicating a decoupling of cognitive processing from the text (see also Rayner & Fischer, 1996; Rayner & Raney, 1996; Schad & Engbert, 2012; Schad et al., 2010; Rabovsky, Alvarez, Hohlfeld, & Sommer, 2008). The levels of inattention hypothesis predicts that during states of weak decoupling high-level (wrap-up) processes should be reduced, but low-level (lexical) influences should be intact. During deep decoupling, however, high- and low-level influences should be reduced.

Predicting mindless reading from eye movements: A major current challenge and chance for mind wandering research is to identify objective and reliable online-markers that allow detecting episodes of mind wandering (including their onset and offset) without relying on subjective self-reports or interfering with task performance (Franklin et al., 2011; Smallwood, in press). Previous findings (Reichle et al., 2010; Smilek et al., 2010b; Uzzaman & Joordens, 2011) suggest that eye movements may be ideally suited for this purpose because they (a) provide a good measure of moment-to-moment cognitive processing and attention (Rayner, 1998, 2009), (b) occur with high frequency in virtually all tasks (Liversedge, Gilchrist, & Everling, 2011), and (c) are relatively easy to record and analyze.

At the same time, it may be difficult to predict mind wandering from eye movements. First, finding that mindless reading predicts measures of eye movements [i.e., a high probability $P(\text{eye}|\text{mindless})$] is not the same as finding that eye movements predict mindless reading [i.e., a high probability $P(\text{mindless}|\text{eye})$], and these two probabilities can be very different.² Here, we use a Bayesian analysis to determine the *posterior* probability, $P(\text{mindless}|\text{eye})$, that a reader is currently in a state of mindless reading given a

recorded eye movement. Second, when observing mean differences between mindful and mindless reading at the level of groups (averaged over participants, trials, and/or individual eye movements) it remains unclear whether mindlessness can be inferred from the eyes at the level of individual eye movements or trials. Such predictions might be difficult to derive, because eye-movement measures exhibit considerable variance (Kliegl, Nuthmann, & Engbert, 2006; Rayner, 1998). Notably, reading fixations crucially depend on the words and sentences being read. However, the design of the present study allows investigating mindless and mindful reading on exactly the same text material, including specific target words.

2. Materials and methods

2.1. Participants and materials

Thirty German high school students, aged between 17 and 20 years, were paid 45 € each to participate in the study. Informed consent was obtained from all participants. All participants had normal or corrected to normal vision. Participants read 50 stories, taken from elementary school textbooks and slightly modified for the experiment (henceforth *Potsdam Mindless Reading Corpus*, PMC). The text corpus comprised about 17,500 words distributed across 216 pages of text.

2.2. Apparatus

In an attempt to create a situation where participants were likely to encounter episodes of mindless reading, readers were seated in a comfortable, laid-back easy chair where they could rest their head on a headrest and their legs on a footstool. An arm mount was positioned for the recording of eye movements, holding an EyeLink 1000 eye tracker (SR Research) in the remote setup and a 17-in. flat panel LCD screen. The monitor was positioned slightly above the eye level of the reader and then tilted downward, so that a reader's line of gaze would be perpendicular to the vertical plane of the monitor. The viewing angle of the monitor and monitor tilt were occasionally adjusted to achieve maximum comfort for each reader. Viewing distance was approximately 50 cm, at which each letter of text horizontally subtended approximately .37 degrees of visual angle. The eye tracker sampled left eye position at a rate of 500 Hz. Readers could move their head freely, but for the most part chose to rest it on the head rest of the chair. The EyeLink remote system tracked possible head movements and corrected measured eye position for these movements. The stories were presented in black against a brown-grey background. A rectangular dark brown-grey frame was drawn around the text to create the impression of reading from a sheet of paper. Monitor brightness was reduced to the minimum.

2.3. Design and errors in the text

Two experiments were conducted in succession. Each experiment required participants to read 25 stories.

² For example, the probability for professors to have a high-school degree, $P(\text{high-school}|\text{professor})$, likely approaches one, while the probability for high-school graduates to become a professor, $P(\text{professor}|\text{high-school})$, is much lower. Treating these probabilities as equal reflects the fallacy of the transposed conditional (Wagenmakers, Wetzels, Borsboom, & van der Maas, 2011).

Sixty-two error sentences were defined at quasi-random locations in the PMC, with each story containing one or two error sentences. For each error sentence, several different versions of similar length were constructed. They contained six different kinds of linguistic errors (including an error-free control condition) and were designed to probe for five different levels of mindless reading (Table 1). Which error type was presented at a given location in the text was varied between readers. This was done within experiments 1 and 2 separately. Importantly, the design allowed us to test the effects of different levels of mindless reading and of mindful reading on the same text material. Across both experiments, errors were presented in 48 out of 62 target locations per participant, resulting in a relatively low average presentation rate of one error per 354 words (equivalent to 4.5 text pages). In the remaining 14 target locations meaningful sentences were presented as a control condition.

2.4. Procedure

The experiment was advertised as “relaxed reading”. Upon arrival, readers were instructed to relax on the chair and to find a comfortable position to sit in. Readers’ task was to read the stories for comprehension, and it was emphasized that they should read in a relaxed manner. Participants were told that the text would sometimes be more or less incoherent. They were informed about the various kinds of errors that might occur and this was illustrated by example sentences. Participants were instructed to press the space bar on the computer keyboard whenever they noticed an error in the text. At the beginning of the experiment, participants read three pages of text for practice, each containing one error. They then read the 50 stories of Exp. 1 and Exp. 2. Between experiments, participants were allowed to take a short break where they could stand up and stretch. Within a given experiment, story order was randomized for each subject. Readers could move forwards and backwards in the text by pressing arrow keys on the keyboard. We allowed readers to move backwards in the text to ease transitions into a relaxed reading mode. Presentation of each page of text was preceded by a fixation check to ensure calibration quality. Successful error detection was defined as pressing the space bar on the keyboard after reading an error sentence and before moving onto the next text page. After reading all texts, participants completed two memory tests, the details of which are not reported here.

2.5. Data processing and analysis

The cognitive parsing algorithm of the SR Research Eye-Link software was used to determine the positions and durations of readers’ individual fixations. Fixations were then assigned to pages and lines of text, individual words, and letters (Supplementary Information). (Generalized) Linear mixed effects models ([G]LMMs, Baayen, Davidson, & Bates, 2008; Kliegl, Masson, & Richter, 2010; Pinheiro & Bates, 2000) were used to test differences between mindless and mindful reading, and the control condition (Supplementary Information). (G)LMMs can be viewed as a

generalization of linear regression and allow estimation of random effects (i.e., effects of factor levels that are randomly sampled from a population; here: participants, words, and text pages) in addition to fixed effects [i.e., effects that are repeatable across experiments and can be either discrete (e.g., experiment number) or continuous (e.g., word frequency)]. For large sample sizes the t -statistic effectively corresponds to the z -statistic. Therefore, for the LMMs (two-tailed testing), we took absolute t values larger than 1.645 to indicate marginal significant effects ($p < .10$), values larger than 1.96 to indicate significant effects ($p < .05$), and t values larger than 2.576 ($p < .01$) or 3.291 ($p < .001$) to indicate highly significant effects (cf. Kliegl, Ping, Dambacher, Yan, & Zhou, 2011).

2.6. Data selection

For analyses of eye movements, errors with an overall detection rate of less than 30% were excluded (12.2%). Eye movements from false alarm trials were discarded. To unconfound mindless reading and skimming we excluded trials in which less than 50% of the words in the error sentence were fixated (4.0% of trials; Supplementary Information), leaving a total of 1793 trials for analyses. Under the assumption that readers were already on/off task on the words prior to the error (Reichle et al., 2010; Smallwood et al., 2007), we first analyzed eye movements in an interval of 14 words preceding each error sentence. Next, we generalized the analyses to different interval sizes using the same selection criteria. Only words on the same page of text as the error sentence and only eye movements made during the first viewing of each page of text were analyzed. Also, in each trial we only analyzed eye movements that were made prior to fixating any of the words from the error sentence so that the analyses did not include data from the error sentence, nor data that was collected after subjects had read the error sentence. (For the measure of the “number of reading passes” we made an exception to this selection criterion and also included fixations made after reading the error sentence.) For the 14-words interval, the selection resulted in a total of 24,528 fixations on 20,498 words and 19,313 first-pass fixations on 15,539 words. (Firstpass fixations include all fixations on a word before the reader makes a regression back to this word or previous words in the text.) To select valid word-based fixation time measures like gaze duration (i.e., the cumulative duration of all first-pass fixations per word), standard criteria used in reading research were applied (e.g., removing calibration problems, blinks, irregular fixation behavior [lines with less than 50% fixated words], first and last fixation per line, long and short fixations and saccades; see Supplementary Information). This procedure resulted in valid gaze durations for 9435 words, including 11,106 first-pass fixations. Overall, there were slightly more words with invalid first-pass fixations during mindless reading (40.9%) than during the control condition (38.9%), and mindful reading (38.7%), mainly because there were more lines with irregular fixation behavior and more calibration problems during mindless reading (Supplementary Information).

3. Results

It took readers an average of 2 h and 45 min (range: 1:40 h–4:20 h) to read all texts.

3.1. Error detection

Readers overlooked 39% of the errors in Exp. 1, and 44% of the errors in Exp. 2. False alarm rate, reflecting responses in the control condition without errors, was 7% in Exp. 1 and 3% in Exp. 2. We used signal detection theory (Wickens, 2002) to assess readers' ability to detect errors (i.e., the sensitivity for errors, d' , reflecting the propensity for mindful reading) and response bias (c). When studying mindless reading we inevitably observe highly imbalanced data. These are adequately handled by (generalized) linear mixed effects models [(G)LMMs], which we used to implement the signal detection analyses (Wright, Horry, & Skagerberg, 2009, Supplementary Information). Experiments did not significantly differ in sensitivity (Exp. 1: $d' = 1.90$; Exp. 2: $d' = 2.15$; $p > .10$) and there was a marginal effect in response bias (Exp. 1: $c = -1.55$; Exp. 2: $c = -1.98$, $z = 1.68$, $p < .10$) reflecting slightly fewer responses in Exp. 2. Sensitivity for errors decreased over the course of Exp. 2 [$\Delta d'$ (per page of text) = -0.014 , $z = -1.94$, $p = .052$], but not across Exp. 1 ($p = .50$; slope-difference between experiments: $\Delta d' = 0.017$, $z = 2.01$, $p < .05$).

Fig. 2 depicts how sensitivity differed between error types (for both experiments: $p < .001$). Planned contrasts revealed that these differences followed the predictions: in Exp. 1, readers were most sensitive to (i) semantic errors, followed by (ii) discourse errors (difference to semantic errors: $\Delta d' = -0.80$, $z = 5.73$, $p < .001$), and (iii) gibberish text (difference to discourse errors: $\Delta d' = -0.31$, $z = 2.40$, $p < .05$). In Exp. 2, readers were most sensitive to

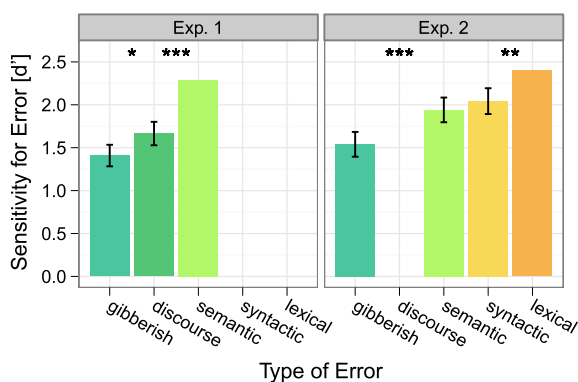


Fig. 2. Sensitivities (d') from a mixed effects signal detection analysis for different types of errors in Exp. 1 and 2. Conditions *lexical* and *syntactic* were not tested in Exp. 1 to discourage strategies other than understanding the text. *Discourse* was not tested in Exp. 2 to focus on levels of deep mindless reading. Conditions are color-coded, ranging from high-level errors (light grey; left) testing weak mindless reading to low-level errors (black; right) testing deep mindless reading. Error bars are SEM from a GLMM testing (sliding) differences in sensitivity between neighboring error types (Venables & Ripley, 2002). (* $p < .05$, ** $p < .01$, *** $p < .001$, – $p > .10$).

(i) lexical errors, followed by (ii) syntactic errors ($\Delta d' = -0.46$, $z = 3.02$, $p < .01$), (iii) semantic errors ($\Delta d' = -0.04$, $z = 0.26$, $p = .79$), and (iv) gibberish text ($\Delta d' = -0.54$, $z = 3.63$, $p < .001$). Thus, readers more easily noticed low-level errors, and were less sensitive to high-level errors. This finding is compatible with the idea that different levels of attentional decoupling led to overlooking of different kinds of errors.

3.2. Analyses of eye-movements

We hypothesized that overlooking an error indicates an episode of mindless reading. Assuming that most of the time readers were already off task on the words before the error (Reichle et al., 2010; Smallwood et al., 2007), we first analyzed eye movements made in an interval of 14 words preceding each error sentence. To test the generality of the findings, follow-up analyses considered different interval lengths. Unless otherwise noted, data from different types of errors and from the two experiments were pooled for analyses.

Global analyses focused on common measures of eye movements used in reading research (Rayner, 1998, 2009). Nine word-based measures of fixation durations and saccade probabilities were computed (Supplementary Information). For the analyses we used (G)LMMs to investigate how fixed effects (like mindless reading) affect measures of eye fixations, and determined regression coefficients, b , to estimate the size of these influences. Unless otherwise noted we used unstandardized regression coefficients, where b estimates the change in the dependent variable given a one-unit change in the independent variable. Out of the nine measures, only one measure significantly differed between mindless and mindful reading: readers read words with fewer passes during mindless reading as compared to mindful reading ($b = 0.10$; $t = 5.0$, $p < .001$). Differences in any of the other eight variables were not significant (Supplementary Information).

Next, we performed local analyses to test whether the influence of lexical and linguistic variables on gaze durations is reduced during mindless reading as compared to mindful reading or the control condition. As can be seen in Fig. 3A sentence- and clause-final words were fixated longer than other words, replicating the wrap-up effect found in many reading studies (Just & Carpenter, 1980; Warren et al., 2009). The average wrap-up effect across all reading conditions (mindful, mindless, and control) was not present in the LMM ($t = -1.47$, $p > .10$; Supplementary Information) after statistically controlling for word length, word frequency, and random between-word variance. Notably, the wrap-up effect was strongly reduced in the mindless reading condition (Fig. 3A), and this difference was significant (wrap-up in mindless versus mindful condition: $b = -18.0$, $t = -1.90$, $p < .10$; control versus mindless: $b = 23.7$, $t = 2.15$, $p < .05$), and did not differ between experiments ($|ts| < 0.8$, $ps > .10$).³

³ Post-hoc tests showed that the difference in the wrap-up effect between the mindful condition and the control did not exceed the level of chance ($t = 0.63$, $p > .10$).

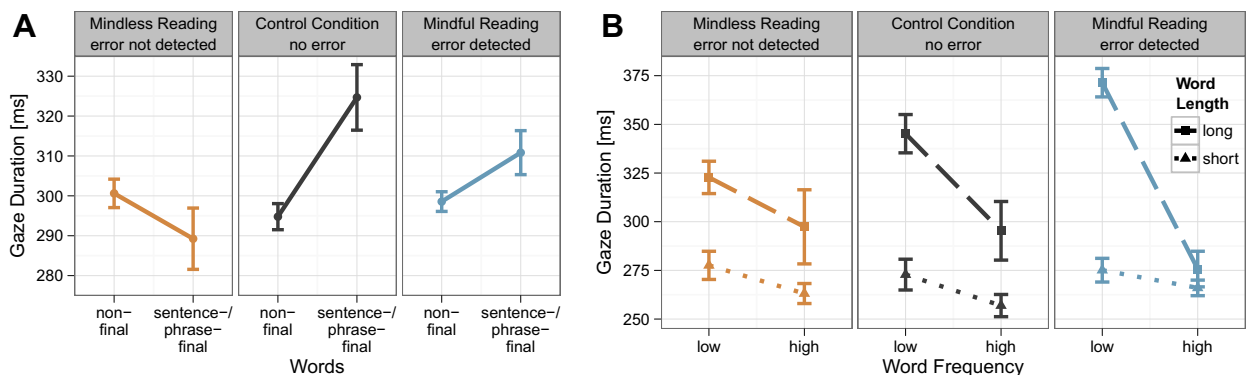


Fig. 3. Influences of high-level and low-level linguistic variables on gaze durations in three reading conditions: mindless reading, a control condition, and mindful reading. Gaze durations were measured on 14 words prior to the error sentence and were residualized for random effects from the LMM; error bars are SEM. (A) High-level wrap-up effect: gaze durations on *sentence-* or *phrase-final* words versus *non-final* words. Data is from both experiments. (B) Low-level lexical effect: modulation of gaze durations due to word length, word frequency, and their interaction in Exp. 2. Short words are six or fewer letters long; word frequencies were median split.

Prior to overlooking errors in Exp. 2, the effects of lexical variables on gaze durations were reduced. As can be seen in Fig. 3B, readers overall looked longer at long words than at short words. They also looked longer at words of low frequency than at words of high frequency, and the effect of word frequency was stronger for long than for short words (all $|ts| \geq 2.9$, $ps < .01$), replicating key findings in reading research (Kliegl et al., 2006; Rayner, 1998). However, these effects were considerably reduced during episodes of mindless reading. Word length ($1/wl$) had a weaker effect on gaze durations during mindless reading than during mindful reading ($b = 155$, $t = 1.93$, $p < .10$) or the control condition ($b = -195$, $t = -1.93$, $p < .10$). The main effect of word frequency ($\log_{10} \text{freq}$) did not significantly differ between mindless reading and mindful reading or the control condition ($|ts| \leq 1.4$, $ps > .10$). The word frequency effect, however, was hardly modulated by word length during states of mindless reading (Fig. 3B, left panel). Statistically, this modulation was much weaker than during mindful reading ($b = -175$, $t = -4.6$, $p < .001$) or the control condition ($b = 92$, $t = 1.95$, $p < .10$). As is visible in Fig. 3B, for long words the frequency effect was strongly reduced during mindless reading ($b = 15$, $t = 2.8$, $p < .01$; for post hoc tests see Supplementary Information). For short words, the frequency effect was not significant during mindful reading, but marginally significant during mindless reading, and the slope-difference was significant. It may be that lexical processing of short words is more automatic and does not require the kind of higher-level attention measured in our paradigm. In summary, lexical processing effects were reduced before errors were overlooked in Exp. 2, indicating episodes of deep mindless reading.

Next, we (a) extended our local analyses presented in Fig. 3 to intervals ranging from 10 to 20 words prior to the error and (b) performed more explicit tests for differences between experiments. When participants were in the initial phase of the reading task in Exp. 1 we expected that during mindless reading cognitive processing might be weakly decoupled from the text. Accordingly, high-level

influences on gaze durations should be reduced but low-level influences may be intact. In contrast, after having spent much time in the lab reading boring texts readers may pay less attention to the reading task in Exp. 2, and cognitive processing may be deeply decoupled during mindless reading. Hence, text processing should fail at all levels of processing and both high-level as well as low-level influences should be decoupled.

Fig. 4 displays standardized regression coefficients representing the relative influences of high-level wrap-up and low-level lexical (word frequency \times length interaction) variables on gaze durations during mindless and mindful reading. The results show that wrap-up effects were reduced during mindless reading (Fig. 4, left panels) for all intervals [marginal ($ts > 1.7$, $ps < .10$) to significant ($ts < 2.1$, $ps > .01$) reduction; 20-words: $t = 1.54$, $p > .10$] and this effect did not significantly differ between experiments ($|ts| < 0.95$, $ps > .10$).⁴ In our previous analyses (Fig. 3B) we had found that in Exp. 2 the word frequency effect was reduced during mindless reading for long words (but not for short words). Fig. 4 (lower right panel) shows that this effect was highly reliable for all intervals ($ts > 2.80$, $ps < .01$; mindful versus mindless reading). However, it was absent in Exp. 1 ($|ts| < 0.63$, $ps > .10$), and the difference between experiments was significant for all intervals ($ts < -1.97$, $ps < .05$). Taken together, for Exp. 1 we observed a dissociation between reduced high-level wrap-up effects and intact low-level lexical effects (Fig. 4, upper panels), which provides support for our expectation that cognitive processing was weakly decoupled when mindless reading occurred in the initial part of the study. For Exp. 2, however, the results indicate states of deep decoupling as both high-level wrap-up effects as well as low-level lexical influences on gaze durations were reduced during mindless reading (Fig. 4, lower panels).

⁴ Note that the coefficients for the wrap-up effect during mindless reading were negative for Exp. 1. The reason for this is unclear. The difference between mindful and mindless reading, however, was as expected.

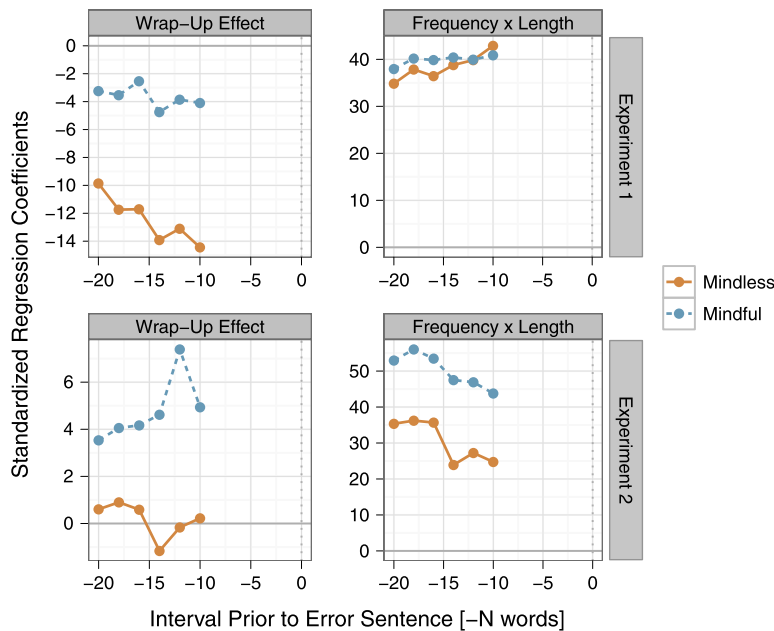


Fig. 4. Effects of high- and low-level linguistic variables on gaze durations during mindless (black, solid line) and mindful (grey, dashed line) reading in Exp. 1 (upper panels) and Exp. 2 (lower panels) for different intervals (N of words) prior to the error sentence. Graphs depict standardized regression coefficients from LMM analyses. For each interval, a separate LMM analysis was conducted and tested whether a given effect differed between mindless and mindful reading. For the high-level wrap-up effect (left panels), positive regression coefficients represent the standard wrap-up effect of longer fixations on final compared to non-final words. For the low-level interaction between word frequency and length (right panels), positive coefficients indicate a stronger frequency effect for long words than for short words.

A central prediction that emerges from the proposed levels of inattention hypothesis is that overlooking different kinds of errors reflects different levels of attentional decoupling. To further test this prediction we analyzed eye movements for different error types. For the analyses we defined three broad categories of error types: (a) high-level errors (gibberish text and discourse errors), (b) medium-level errors (semantic and syntactic errors), and (c) low-level errors (lexical errors). This aggregation helped to reduce complexity and to improve the stability and reliability of the LMM analyses. We then generated a statistical measure for attentional decoupling: for the high-level wrap-up and the low-level lexical variable, we determined the influence of this variable on gaze durations (by computing the standardized regression coefficient in an LMM). Next, we determined how this influence differs between mindless and mindful reading. The resulting difference-value (coded as an interaction between lexical/linguistic influences and mindless reading) represents a direct statistical measure for attentional decoupling: Negative difference-values indicate that linguistic influences on eye movements are reduced when errors are overlooked. Based on the levels of inattention hypothesis we predict that for low-level errors decoupling should be observed for low-level (lexical) and for high-level (wrap-up) influences, whereas for high-level errors high-level wrap-up effects should be reduced, but low-level lexical effects should be relatively less affected.

For the high-level wrap-up effect (Fig. 5, left panel) the results suggest that decoupling was present for overlooking of all error types (negative difference-values), and the

effect did not significantly differ between error categories (for all intervals: $\chi^2(2) < 1.6$, $ps > .47$). This finding suggests that when any type of error is overlooked high-level processing is decoupled from the text. (Note that the wrap-up effect is overall smaller in size compared to the word frequency \times length interaction.) For the low-level lexical influences (Fig. 5, right panel) the results show that the influence of word frequency and length was strongly reduced when low-level errors were overlooked, but were only slightly affected when high-level errors were overlooked. The difference between error categories was significant for all intervals larger than 12 words ($\chi^2(2) > 5.7$, $ps < .06$). These findings support our hypothesis that overlooking different types of errors in the SAST reflects graded levels of attentional decoupling: overlooking low-level errors indicated a state of deep decoupling as both high-level and low-level influences on eye movements were reduced. Overlooking high-level errors, to the contrary, indicated a state of weak decoupling as eye movement markers for high-level integration processes were reduced, but low-level lexical processes were intact.

3.3. Predicting mindless reading from eye movements

Is it possible to infer from the ongoing eye movements whether readers are currently paying attention to the text? To investigate this question, we selected a subset of the data where we expected the strongest effects of mindless reading. Our results suggest that effects of mindless reading on eye movements are most pronounced for lexical processing of long words (Fig. 3B). For the analyses we

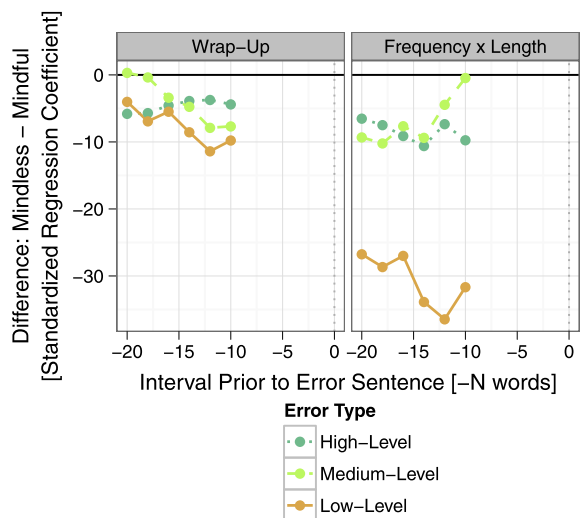


Fig. 5. Differential effects (mindless versus mindful reading) of high-level and low-level variables on gaze durations for different categories of errors. The graphs show how standardized regression coefficients representing the influences of high-level wrap-up (left panel) or low-level lexical (right panel; word frequency \times length interaction) variables differ between trials where errors were overlooked (mindless reading) versus detected (mindful reading). Negative difference-values indicate that the influence of linguistic variables on gaze durations is reduced during mindless reading, reflecting attentional decoupling. High-level errors (light grey, dotted lines) are gibberish text and discourse errors, medium-level errors (dark grey, dashed lines) are semantic and syntactic errors, and low-level errors (black, solid lines) are lexical errors. Regression coefficients are from LMMs for different intervals of words prior to the error sentence.

used gaze durations on very long target words (≥ 10 letters), which were located an average of 13.4 words prior to the upcoming error in the text. In addition, we focused our analysis on lexical errors because these should best capture reduced lexical processing (cf. Fig. 5). As is visible in Fig. 6A + B, distributions of gaze durations on target words considerably differed between deep mindless as opposed to mindful reading, and the direction of the effect was consistent with the general findings reported above. During mindful reading we observed a standard word frequency effect, as gaze durations on low-frequency words were considerably prolonged and gaze durations on high-frequency words were shortened. To the contrary, when lexical errors were overlooked during deep mindless reading target word frequency did not clearly modulate the distribution of gaze durations.

Based on these clear-cut results, we performed a Bayesian analysis to predict mindless reading from the gaze durations readers made on specific target words. Based on the graded nature of decoupling, we estimated the prior probability for mindlessness, $P(\text{mindless})$, from the overall rate with which errors were overlooked in Exp. 2. The posterior probability for mindless reading given a certain eye fixation, $P(\text{mindless}|\text{gaze})$, was determined via Bayesian logistic regression (Gelman, Jakulin, Pittau, & Su, 2008). We found that the posterior probability for mindless reading was low when readers' eyes responded to the lexical difficulty of the target word: mindless reading was least likely

when readers made long gaze durations on low frequency target words [$P(\text{mindless}|\text{low freq, gaze} \geq 500 \text{ ms}) = .33$, for continuous predictions see Fig. 6C + D] or when they made relatively short fixations on high frequency target words [$P(\text{mindless}|\text{high freq, gaze} < 500 \text{ ms}) = .42$]. To the contrary, the probability for mindless reading was high when readers' eyes did not respond to the lexical difficulty of the target word: failing to slow down the eyes on difficult low-frequency words predicted mindless reading [$P(\text{mindless}|\text{low freq, gaze} < 500 \text{ ms}) = .60$]; likewise, failing to speed up on easy high frequency words was an indicator for an absent mind [$P(\text{mindless}|\text{high freq, gaze} \geq 500 \text{ ms}) = .63$].

From the posterior probability for mindless reading (Fig. 6C + D) we predicted error detection in the error sentence: We predicted mindless reading when the posterior probability for mindless reading exceeded a critical threshold, and predicted mindful reading when the posterior probability fell below the critical threshold. We used different prediction thresholds, corresponding to different prior expectations for the occurrence of mindless reading, to predict different levels of decoupling. Predictions were successful and significant for a wide range of decision thresholds and reached up to 68.3% correct predictions for deep mindless reading (see Fig. 6E). This finding demonstrates that an individual fixation duration measured on a specific target word in real time can be highly informative about whether a reader's attention is currently focused on the text, or whether it is wandering.

Notably, given the average total reading time of 356 ms and the average target word-error distance of 13.4 words, we predicted overlooking of lexical errors an average of 4.8 s before they occurred in the text. This finding suggests that the actual accuracy with which eye movements measure states of mindless reading should be higher than the current estimate of 68.3%. Moreover, predictions were based on information from individual gaze durations readers made on individual target words, and predictions may be further improved by combining information from several words in a trial and from multiple eye movement measures.

4. Discussion

In the current study, we investigated episodes of mind wandering during reading, where cognitive processing is decoupled from the text as external attention is reduced. Coupled and decoupled processing are often treated as a dichotomy. The central aim of the present work was to introduce the levels of inattention hypothesis, which proposes graded attentional decoupling at hierarchical levels of cognitive processing. To measure levels of attentional decoupling we developed the sustained attention to stimulus task (SAST), a behavioral measure for mindless reading, which is based on readers' sensitivity for errors in the text. We tested predictions from the levels of inattention hypothesis and the cascade model of inattention by performing detailed and reliable analyses of a large corpus of eye-movement data during mindless reading. We found that eye movements were decoupled from low-level and

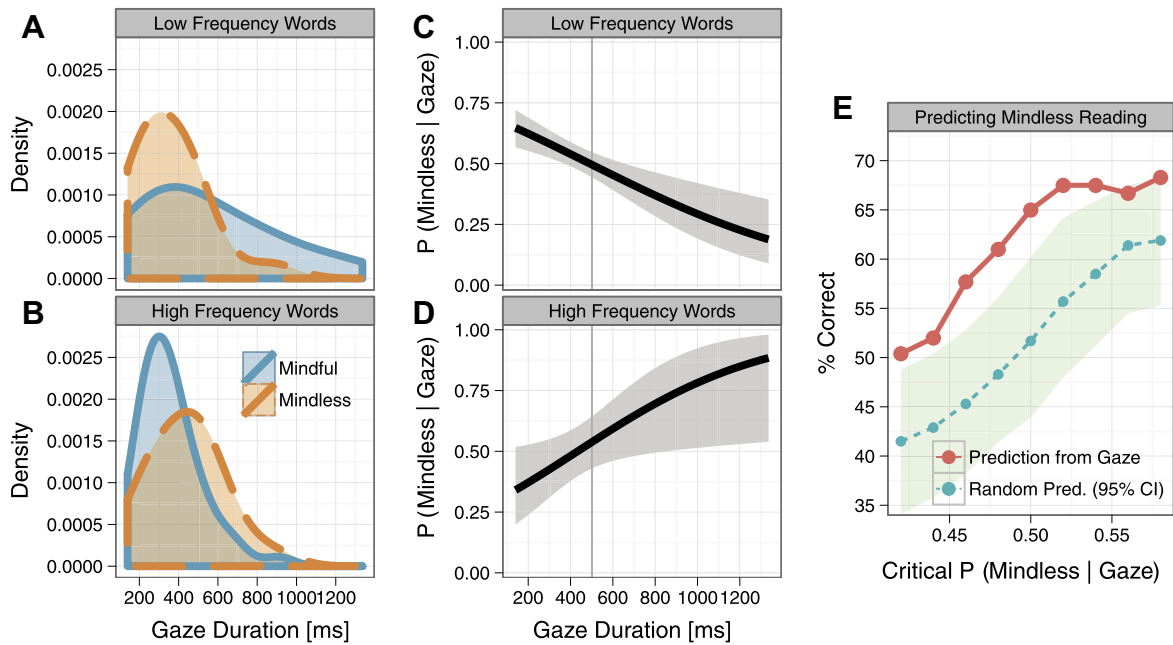


Fig. 6. Predicting states of mindless reading from gaze durations on low-frequency words (panels A and C) and on high-frequency words (panels B and D). Mindless reading is defined as overlooking a lexical error in the upcoming error sentence. Gaze durations are on long words (≥ 10 letters) from the 14 words prior to the error sentence. A and B: Distributions of gaze durations (estimated densities) during mindful (solid grey line) and mindless (dashed black line) reading. C and D: Posterior probability for mindless reading [point estimates (posterior modes) and SEM] as a function of gaze duration, estimated via Bayesian logistic regression with an informed intercept-prior derived from the overall probability to detect any kind of error in Exp. 2, and Cauchy priors for all other parameters. A to D: Log10 word frequencies per million were split at the value zero. E: Percent correctly predicted states of mindless reading (black dots, connected by solid line), where higher prediction thresholds, $P(\text{Mindless}|\text{Gaze})$, correspond to deeper predicted levels of mindless reading. Random predictions ($N = 1000$) provide a statistical baseline with 95% confidence intervals (dashed grey line and light grey ribbon).

high-level linguistic variables in a hierarchically graded fashion before errors were overlooked. In a Bayesian analysis, we demonstrated that it is possible to use eye movements to predict overlooking of errors 5 s before they occur, and this suggests that eye movements provide an unobtrusive online-indicator for mind wandering. Our findings support the levels of inattention hypothesis and validate the SAST as a behavioral measure of mindless reading.

Attentional decoupling in the SAST: As a main result, we found that readers overlooked errors about 40% of the time. What factors caused readers to overlook these errors? First, the percentage of overlooked errors is compatible with the estimated amount of time people spend mind wandering in everyday life (Kane et al., 2007; Killingsworth & Gilbert, 2010), suggesting that we were successful in creating task conditions to investigate mindless reading in the eye-tracking laboratory. Second, mind wandering is known to become more frequent with increasing time on task (Schnitzer & Kowler, 2006; Smallwood et al., 2007; Smallwood & Schooler, 2006) and we replicated this finding in our data. Third, we controlled for skimming as an alternative explanation, and found global eye movement measures to be unaffected when errors were overlooked. Indeed, during mindless reading fixations were sometimes longer (cf. Reichle et al., 2010) and sometimes shorter (cf. Franklin et al., 2011) compared to mindful reading depending on whether high or low frequency target words were fixated. These findings indicate

that errors may have been overlooked during episodes of mindless reading because cognitive processing is decoupled from the text.

We included different types of errors in the text to measure different levels of mindless reading. The levels of inattention hypothesis predicts that readers should be very sensitive to low-level errors and less sensitive to high-level errors. This prediction was supported by the experimental findings. Readers quite often overlooked high-level errors, like discourse errors and gibberish text. In these cases, high-level text processing may have ceased during episodes of weak mindless reading. Supporting evidence for this interpretation comes from the observation that low-level errors, like lexical and syntactic errors, were rarely overlooked. This finding is compatible with the interpretation that low-level linguistic processes like word recognition or syntactic parsing may be disrupted when low-level errors are overlooked, indicating episodes of deep mindless reading. Collectively, these results are compatible with the levels of inattention hypothesis. However, the alternative dichotomy-hypothesis can explain differences in sensitivity between error types by assuming differences in the durations of mind wandering episodes. The present eye movement analyses help distinguishing between these explanations.

Decoupling of eye movements: To investigate more closely how text processing changes when errors are overlooked, we performed local eye movement analyses. During mindful reading, readers slowed down to integrate words toward the end of phrases and sentences.

Interestingly, this wrap-up effect was absent before errors were overlooked. This finding suggests that during mindless reading readers overlooked errors in the text because they did not integrate words to construct sentence meaning and to comprehend the text. Moreover, during mindful reading fixation durations were modulated by variables word length and frequency, which constitute empirical markers for word recognition processes. In contrast, before overlooking of errors (Exp. 2) these effects were clearly reduced (Figs. 3–5), and sometimes completely absent (Fig. 6). This finding suggests that errors were overlooked during deep mindless reading because processes of word recognition were incomplete. Importantly, mindless reading affected eye movements on up to 20 words preceding an error sentence (Figs. 4 and 5). Thus, overlooking of errors did not occur because text processing was locally reduced when reading a single sentence or word. Instead, readers' minds were drifting off task over an extended period of time prior to encountering an error. In sum, the present findings suggest that overlooking errors in the SAST indicates episodes of attentional decoupling during mindless reading, where errors are overlooked because text processing is reduced.

While the present results suggest that overlooking errors in the SAST indicates episodes of mindless reading, there may be other specific factors that also contribute to overlooking of errors. Some of these may result from an absent mind; for example, monitoring of text comprehension (Palincsar & Brown, 1984; Smallwood et al., 2007) or memory for task instructions (McVay & Kane, 2009) may be reduced during mindless reading, and may cause readers to overlook errors in the text. Moreover, factors unrelated to mind wandering may lead to overlooking of errors, and may inflate our estimates for the occurrence of mind wandering. Also, decoupling of eye movements from the text may partially result from differences in reading ability or strategy between subjects. It should be noted, however, that we controlled for such effects in the LMM analyses. Importantly, the present eye movement results demonstrate that overlooking an error was preceded by a period of reduced cognitive text processing, indicating an episode of attentional decoupling.

Hypotheses on the nature of attentional decoupling: We derived several predictions from hypotheses of attentional decoupling (Fig. 1) and tested these by analyzing eye-movement data. Critically, the levels of inattention hypothesis predicts states of weak attentional decoupling, where high-level processes are decoupled from the external environment, but low-level processes are still intact. We found eye-movement evidence for weak decoupling in Exp. 1. Here, wrap-up effects, as a measure for high-level integration processes, were reduced when errors were overlooked, but low-level lexical processes (i.e., the frequency \times length interaction) remained unaffected. Deep mindless reading, to the contrary, was observed in Exp. 2, when readers had already spent much time in the lab reading boring texts. Here, not only high-level wrap-up, but even low-level lexical effects were reduced before errors were overlooked. As predicted by the cascade model of inattention (Smallwood, 2011; Smallwood et al., 2007), the consequences of the low-level decoupling in Exp. 2 may have cascaded into the cognitive system to impair higher-level

wrap-up processing. These results demonstrate that graded states of weak (Exp. 1) and deep (Exp. 2) attentional decoupling can be distinguished. This finding is incompatible with a dichotomous view on attentional decoupling and provides support for the levels of inattention hypothesis.

A central prediction from the levels of inattention hypothesis is that overlooking different types of errors reflects different levels of attentional decoupling. The eye-movement data lend support to this prediction. When low-level (lexical) errors were overlooked, eye movements were decoupled from low-level (lexical) variables, and – as predicted by the cascade model of inattention (Smallwood, 2011; Smallwood et al., 2007) – also high-level (wrap-up) influences were reduced (Fig. 5). When high-level errors (discourse errors and gibberish text) were overlooked, however, then decoupling was present only for high-level integration processes (reduced wrap-up effect), but low-level lexical processing was barely affected. These eye movement results suggest that overlooking of low-level errors may indicate states of deep attentional decoupling, whereas overlooking high-level errors may indicate states of weak decoupling. These findings support the levels of inattention hypothesis and the cascade model of inattention, but are incompatible with the dichotomy-hypothesis.

As noted above, the dichotomy-hypothesis of mind wandering may explain differences in sensitivity between error types by assuming variable durations rather than variable degrees of attentional decoupling. For example, task focus during the reading of a single pseudo-word is sufficient to detect the lexical error, and the error can be detected even if attention switches quickly between mindless and mindful reading. Thus, overlooking low-level errors may reflect short-lived episodes of decoupling. To the contrary, to detect high-level discourse errors, attention must be devoted to the text during reading of at least two adjacent sentences, and overlooking high-level errors may thus indicate longer episodes of decoupling. These predictions from the dichotomy-hypothesis were not supported by the present eye movement results: fixation durations were decoupled from cognitive processing up to 20 words before encountering an error sentence, and this interval was similar (or even longer) for low-level errors (see Fig. 5). The eye movement findings therefore suggest that overlooking low-level errors was not only associated with deeper decoupling, but potentially also with longer episodes of attentional decoupling compared to high-level errors. Both of these findings are incompatible with the dichotomous view of attentional decoupling, and are consistent with the levels of inattention hypothesis.

5. Conclusions

Cognitive science has generated theoretical models that describe different aspects of reading (Engbert et al., 2005; Graesser et al., 2002; Reichle et al., 2009; Staub, 2011) and cognition in general (Cohen, 2000; Craik & Lockhart, 1972; Gazzaniga, 2009) as hierarchically organized processes, where information is represented and processed at various lower and higher levels. A long research

tradition has investigated how attention affects processing at such early and late levels (Broadbent, 1958; Deutsch & Deutsch, 1963; Driver, 2001), and the field seems to agree on a continuously graded rather than a dichotomous view of attentional selection (Chun et al., 2011; Mangun & Hillyard, 1995; Treisman, 1960). Here, we investigated how cognitive processing at different levels becomes decoupled from external information when the mind wanders away from an external reading task. Our results indicate that attentional processes during reading may be of a hierarchically graded nature. Low-level processes turned out to be quite robust against lapses in external attention and seemed to fail only when the mind was deeply absent from the current task. High-level text integration processes, to the contrary, seemed to be far more fragile and drifted off the reading task with high frequency. This result supports hierarchical models of reading and cognition. The levels of inattention hypothesis together with the cascade model of inattention provide a framework to understand and describe graded attentional decoupling at such different levels. Importantly, our findings suggest that the level of inattention may strongly vary between experiments, between experimental conditions, or measures of mind wandering, and what level of inattention is assessed in a specific study may strongly influence experimental results. Therefore, to understand and avoid potential inconsistencies, we suggest that it may be helpful to explicitly measure the depth or degree of decoupling in future studies.

Questions for future research: Our findings raise a new, important and open theoretical question: What factors cause decoupling at a specific weak or deep level? Based on previous theorizing, we speculate about possible causes. First, executive control processes may fail (McVay & Kane, 2009, 2010) to varying degrees and controlled high-level processes may be reduced more readily than more automatic low-level processes (Shiffrin & Schneider, 1977). Second, one question is how stimulus independent thought (SIT) is related to the graded levels of attentional decoupling. One possibility is that similar to attentional decoupling, SITs are graded in nature. Another is that SIT emerge only at a particularly deep level of decoupling. Third, the adaptive gain theory of norepinephrine function (Aston-Jones, Rajkowski, & Cohen, 1999) has been proposed as a neurophysiological basis for mind wandering (Smallwood et al., 2011, 2012), and different levels of inattention may result from different degrees of drowsiness and inactivity (“off” state of low locus coeruleus [LC] activity) versus increased vigilance and labile attention (“tonic” mode with high baseline LC activity). Fourth, people may become aware of their wandering mind (Schooler, 2002; Schooler et al., 2011) more easily when their cognitive processing is deeply decoupled from the external environment (as opposed to when it is only weakly decoupled), and they may therefore direct their minds back on task more often.

Another important question for future research concerns the relation of behavioral measures of attentional decoupling (like the SAST) to more subjective aspects of mind wandering. For example, our findings may trigger research to vigorously test the view that SIT is a dichotomous (versus graded) process, and to learn about how graded decoupling is related to (graded or dichotomous) aspects

of SIT. Likewise, in self-report studies of mind wandering it is possible to assess whether participants are meta-aware about their mind wandering (Schooler, 2002; Schooler et al., 2011). In fact, a recent fMRI study (Christoff et al., 2009) found that deeper levels of mind wandering [measured as increased activity in the default network and in the executive system (also see Christoff, 2012)] may be associated with lack of meta-awareness, and this suggests that our paradigm may have the potential to capture subjective awareness of mindless reading in an objective behavioral measure.

Predicting mindless reading from eye movements: As a novel contribution, we demonstrated that gaze durations predicted overlooking of lexical errors 5 s before the error occurred in the text. Thus, recordings of individual eye movements can predict in real time whether a reader is currently in a state of mindless reading at the level of an individual trial. Such a measure may prove highly useful in diverse applications. Objective measures are useful to investigate mindlessness in populations unable to report about their wandering mind, like children or psychiatric patient groups. They could potentially be used to identify and overcome mind wandering in educational or professional settings. They could serve to diagnose individual differences in mind wandering, to objectively evaluate the quality of different texts, or to detect mindlessness in cognitive experiments or crucial real-world tasks like driving (D’Orazio, Leo, Guaragnella, & Distanto, 2007) or closed-circuit television (CCTV) monitoring. In research on reading, detecting mindlessness online allows to apply sophisticated eye tracking techniques, like gaze-contingent display changes (McConkie & Rayner, 1975; Rayner, 1975, 1998), during mindless reading to investigate in detail how text processing changes when readers’ minds are off task. Finally, objective measures are highly valuable tools for studying mind wandering – when investigating factors influencing the propensity to mind wandering (Sayette, Reichle, & Schooler, 2009; Sayette, Schooler, & Reichle, 2010), the consequences of off-task thought (Killingsworth & Gilbert, 2010; Smallwood, McSpadden, & Schooler, 2007), the neural structures (Buckner et al., 2008; Christoff et al., 2009; Mason et al., 2007) and cognitive processes (Levinson et al., 2012; McVay & Kane, 2010; Smallwood, 2010b; Smallwood & Schooler, 2006) that initiate, terminate, and support mind wandering and the default mode.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at <http://dx.doi.org/10.1016/j.cognition.2012.07.004>.

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