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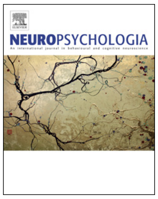

I must have missed that: Alpha-band oscillations track attention to spoken language

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A R T I C L E I N F O

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A B S T R A C T

Attention is critical to the construction of mental representations of language context during comprehension. We investigated the consequences of momentary lapses in attention during listening comprehension on neural activity and behavior. Participants listened to two full-length stories while EEG was recorded, and afterwards completed multiple choice comprehension questions. Listening was periodically interrupted by attention probes, in which participants were asked whether their attention immediately preceding the probe's appearance was focused on the story. The results showed that (1) participants spent a substantial amount of time off-task, endorsing attention lapses on over 30% of probes; (2) for probes on which an attention lapse was endorsed, later accuracy on comprehension questions querying pre-probe information was decreased; (3) the pre-probe period just before the endorsement of an attention lapse was characterized by a greater percentage of above-threshold oscillations in the alpha-band (8–12 Hz) compared to just prior to the endorsement of on-task or split-attention listening; and (4) when participants made "I have no idea" responses to comprehension questions, their EEG record revealed a greater percentage of above-threshold alpha oscillations during the original presentation of the information queried by the comprehension questions, compared to correct responses or incorrect guesses. These results connect changes in neural activity in the alpha band to episodes of mind-wandering during listening comprehension, and in turn to decreased comprehension accuracy. This demonstrates how alpha can be used to track attentional engagement during language comprehension, and illustrates the dependence of successful language comprehension on attention.

1. Introduction

Language comprehension is a complex cognitive process that draws upon a number of sub-processes, both specialized (e.g. decoding words from a speech stream) and more general (e.g. maintaining information in memory). This is reflected by most theoretical accounts of language comprehension (e.g. Gernsbacher, 1997; Long et al., 2006; Perfetti, 2007). Critical to successful comprehension is the ability to focus and maintain attention to a task, or attentional control, an aspect of goal maintenance. However, while attention to the task might be assumed to be a "prerequisite" for successful comprehension, it has not traditionally been directly measured or accounted for in studies of language processing. Recently, however, the rapidly growing mind-wandering literature has demonstrated that individuals spend quite a lot of time mind-wandering while performing cognitive tasks, including up to 50% of the time during language comprehension (Franklin et al., 2011; Giambra, 1995; Smallwood et al., 2008b; Uzzaman and Joordens, 2011). Indeed, recent studies have shown how brief lapses in attention have a significant negative impact on performance on multiple choice comprehension tests (Smallwood et al., 2008b), and may account for a substantial portion of individual differences in comprehension (McVay and Kane, 2012a, 2012b). However, the neural mechanisms underlying such lapses in attention and their link to comprehension-based performance have yet to be established.

One candidate neural mechanism is oscillatory activity in the alpha-band (~8–12 Hz), which has been related to changes in attentional focus going back to some of the earliest published EEG studies (Adrian, 1944; Adrian and Matthews, 1934; Berger, 1929). In studies of human cognition, alpha has often been considered to be a marker of inattention or "cortical idling" (Pfurtscheller et al., 1996), and therefore, in many ERP studies, to be a nuisance and "source of noise" in the data (Luck, 2014). Recently, however, many studies have begun to focus on the functional significance of alpha during cognitive processing, and have suggested that alpha activity reflects the active inhibition of sensory stimuli (Klimesch, 2012; Romei et al., 2010; Roux and Uhlhaas, 2014), a form of communication across brain areas (Saalmann et al., 2012;

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Wang et al., 2012), and that it is modulated in concert with activity in other bands to optimally process perceptual input (Arnal and Giraud, 2012; Samaha et al., 2015). One reliable finding that these somewhat differing accounts all seek to explain is that increased alpha in scalp-recorded EEG is associated with the direction of attention inward, away from external stimuli (Jensen et al., 2002; Jensen and Mazaheri, 2010; Mazaheri and Jensen, 2010; Roux and Uhlhaas, 2014; Strauß et al., 2014; Weisz et al., 2011; Wilsch and Obleser, 2016). Following from these findings, we have reasoned that for tasks in which attention must be directed towards external stimuli for successful performance, increased alpha activity might serve as an index of lapses in attentional control. Language comprehension is an example of an everyday cognitive task that depends upon the processing of external input (e.g. an incoming speech stream), and therefore it may be possible to use fluctuations in alpha activity to examine fluctuations in attention during comprehension. Consistent with this reasoning, we recently found that relative increases in alpha power during spoken language comprehension were associated with reductions in ERP indices of language processing (Boudewyn et al., 2017a, 2015).

However, in these studies we did not have explicit measures of either mind-wandering or comprehension outcome. Indeed, to our knowledge, no previous studies have used attention probes to directly link comprehension performance to lapses in attention and alpha oscillations, although some previous studies have combined attention probes with EEG measures to demonstrate that periods of mind-wandering are accompanied by reductions in visual attention and perceptual processing (e.g. Baird et al., 2014; Smallwood et al., 2008a). It has therefore not been possible to confirm that periods of relatively high alpha activity during comprehension correspond to lapses in attention, and most importantly, whether this ultimately leads to poor comprehension. In order to make these links, in the current study we included explicit measures of attention to the task (attention probes) and of comprehension outcome (multiple choice questions targeting pre-probe information) and recorded EEG during story listening. Participants listened to two full-length detective stories, chosen because they provided a naturalistic vehicle for presenting concrete pieces of information (clues) critical to comprehension. This design allowed us to directly investigate the neural signature associated with lapses in attention during language comprehension, and to connect this to behavioral outcome measures of successful comprehension.

2. Materials and methods

2.1. Participants

44 participants (14 male) gave informed consent and took part in this study, which was approved by the University of California Davis' Institutional Review Board. All were right-handed, native speakers of English, with no reported problems with hearing or reading, nor any neurological/psychological disorders. All were compensated with course credit. The average age of participants was 20.38 (range: 18–27).

2.2. Materials

Participants listened to two full-length short stories. These were adapted from the Sherlock Holmes canon (*The Three Students* (Doyle, 1905) and *The Emerald Crown* (Doyle, 1992)). Stories were adapted to conform to modern vocabulary and syntax norms, for ease of listening. Runtime was 72.8 min total (*The Three Students*: 34.4 min; *The Emerald Crown*: 38.4 min). Stories were spoken by a female, with natural inflection and at a natural speaking rate, and were digitally recorded using a Schoeps MK2 microphone (44,000 Hz, 16 bit).

Stories were interrupted by 54 probes over the course of the session (*The Three Students*: 25; *The Emerald Crown*: 29). The average time between probes 1.36 min for *The Three Students* (range: 0.78–2.13 min) and 1.39 min for *The Emerald Crown* (range: 0.47–2.21 min). Probes read: "Just prior to this question, was your attention on-task or off-task?" and given the following response options: "On Task", "Off task unaware (zoning out)", and "Off task aware (tuning out)".

Two multiple choice comprehension tests were created to query pre-probe information (*The Three Students*: 46 questions; *The Emerald Crown*: 31 questions). Each question was designed to correspond to specific information presented immediately before each probe. When possible, as when multiple pieces of information were presented just prior to a probe, multiple questions were created accordingly. Participants responded by circling one of 5 possible responses to each question: responses A, B, C, and D contained the correct response and foils; response E was "I have no idea".

3 participants were excluded from all analyses because they exclusively made On-Task responses to the attention probes, and 1 participant was excluded for making no errors on the multiple choice comprehension tests. 6 additional participants were excluded for making no "No Idea" responses on the multiple choice comprehension tests. Thus, N = 34 for all analyses reported below.

2.3. Procedure

Once being fitted with the EEG cap and facial electrodes, participants were seated in a comfortable chair in an electrically-shielded, sound-attenuating testing room. An experimenter read task instructions, including a description with examples of each of the response categories to the attention probes ("on task", "off-task unaware" and "off-task aware"). Off-task Unaware was described as a state of "zoning out", such as when you don't realize that you are thinking about something else until you catch yourself later. Off-task Aware was described as a state of partial "tuning out", such as when you realize that you are thinking about something besides the task, but you continue to do both anyway. Below, we refer to these states as "On-Task", "Zoned Out" and "Split-Attention." Participants were explicitly told that off-task thought is a common and normal occurrence while reading or listening, and were encouraged not to be embarrassed if they should find themselves off-task. Participants were asked to respond to the attention probes truthfully based on their attentional state just before the probes interrupted the stories.

A white fixation cross was presented in the center of a black screen, about 100 cm in front of participants, and was present throughout listening, except when replaced by the attention probes. Story order was counterbalanced across participants. After listening to both stories, participants completed two paper-and-pencil multiple choice comprehension tests, one for each story.

EEG was recorded from 29 tin electrodes, mounted in a custom elastic cap (ElectroCap International). The right mastoid was used as the recording reference (except for four electrodes used to measure eye movements: one electrode above and one below the left eye were referenced to each other, and two placed on the outer canthi were referenced to each other). The left mastoid was used off-line for algebraic re-referencing to the average of both mastoids. EEG was amplified with bandpass cutoffs at 0.05 and 100 Hz and digitized at a sampling rate of 500 Hz, later downsampled to 250 Hz. Impedances were kept below 5 kΩ. Data processing and analysis was performed using SCAN (Compumedics Neuroscan) and MATLAB, using the EEGLAB toolbox with ERPlab plugin, and custom scripts. Segments of data containing large movement-related artifacts were discarded. ICA artifact correction was used to correct for eye-blinks. On average, 2.4 ICA components were selected for removal (range: 1–6).

3. EEG time-frequency approach

In this study we made use of the BOSC/p-episode approach to quantify alpha activity during story listening. This approach detects "true" oscillatory events (i.e. oscillations that exceed amplitude and duration thresholds) listening task (Caplan et al., 2003; Hughes et al., 2012; Watrous et al., 2013). We selected this method because is allowed us to bypass a significant methodological challenge to studying oscillatory activity associated with lapses of attention; namely, that lapses are not particularly likely to share onsets, offsets or durations across instances. For example, we might know that a lapse occurred during the pre-probe period of Trial X, but it may or may not have lasted for the entire pre-probe period, and if not, its time-course may or may not overlap with a lapse that occurred during the pre-probe period of Trial Y. While most other methods of time-frequency analysis require the selection of a specific time window across which to average a signal such as amplitude across trials and participants, the current approach allowed us to instead quantify the percentage of time in the pre-probe period in which above-threshold alpha activity was present. This is not to say that the amplitude of this activity is an irrelevant measure; on the contrary, our own previous work suggests that lapses in attention during listening comprehension may be characterized by relatively high amplitude alpha (Boudewyn et al., 2017a, 2015). However, BOSC/p-episode provided an ideal measure for the present purposes, in which we sought to link changes in alpha oscillations to attentional state and to later comprehension on a trial by trial basis.

This approach uses wavelets to perform time-frequency decomposition, regressing out the background 1/f noise signal (here, we excluded 95% of the estimated background noise signal) (see Caplan et al., 2003 for additional details on this method). The signal is then subjected to duration threshold criteria by providing a user-defined number of cycles that are required for activity at a given frequency to be considered to be oscillatory (e.g. 2 cycles). Data-points that exceed these power and cycle duration thresholds are marked as oscillatory events. This allows for the calculation of the percentage of time in a given segment of data that oscillatory activity exceeding these user-defined thresholds is present in a given frequency band. This method is particularly useful for investigating oscillatory activity that may vary in time-course across trials (Cohen, 2014). This was our primary motivation for choosing this method of time-frequency analysis, as we expected the duration and specific time-course of attention lapses to vary (e.g. some lapses may last longer than others, or begin earlier than others with respect to the probes). The BOSC/p-episode method allowed us to quantify changes in the amount of pre-probe time in which above-threshold alpha oscillations were present as a function of probe response, without having to select a specific time-window within our pre-probe search space or average across all pre-probe time-points.

Therefore, for each electrode we used the BOSC/p-episode method to generate a binary vector representing the time-series for the entire experiment. Each data-point in this vector indicated whether or not an oscillatory event was present at that time-point, defined according to the power and duration threshold criteria described above. We then extracted the segments of this time-series that corresponded to the pre-probe period of each attention probe, and examined this pre-probe data as a function of attention probe response (On-Task, Zoned Out, and Split-Attention) and multiple choice comprehension question response (Correct, Incorrect-Guess, No Idea). Five seconds was chosen for the duration of the pre-probe period in order to capture the average duration of the two sentences immediately preceding the probe. Importantly, information that was critical to correct responding on the multiple choice comprehension test that followed EEG recording was presented during this pre-probe period. Thus, the EEG measure we used in the analyses below was the percentage of the pre-probe period in which above-threshold alpha oscillations were detected.

3.1. *Relating changes in attentional state to "trials"*

One challenge to studying attention lapsing is the number of trials that are available to analyze, as participants cannot be assigned to an attention lapse condition, but must instead be relied upon to lapse (which they do, as we observe below, a substantial proportion of the time). In addition, there is a practical limit to the number of attention probes that can be included in the task, as highly frequent probing would not give participants adequate time in which to lapse (here, we ensured an average of 1.36 min of listening time between probes). Thus, our approach differed from many EEG time-frequency and ERP studies in that it was tailored to examine changes in oscillatory activity that unfold over relatively long periods of time with varying time-courses and which cannot be controlled by the experimenter.

To do so, we used a relatively long pre-probe period to encompass the entirety of the two sentences in which key pre-probe information was presented (5 s). This provided a segment of the full time-series that was 1250 data-points in length for a given pre-probe period. The number of data-points for a given pre-probe period was determined by its duration multiplied by the sampling rate ($5 * 250 = 1250$). It should be noted that there are many ways to interrogate this data that would seem to change the number of "trials" available for analysis. For example, the pre-probe period could be broken into one-second segments, the percentage of above-threshold alpha calculated for each one, and the average used as a dependent measure. This would give the illusion of a five-fold increase in the number of "trials" for a given attentional state. Or, the percentage of above-threshold alpha could be calculated for the portion of the pre-probe period corresponding to the individual words within it, which would seem to increase the number of "trials" by even more. However, as can be seen with these examples, these amount to different ways of segmenting the very same time-series. In short, there are ways to segment the pre-probe period that would give the appearance of very large numbers of trials, but this would be rather misleading.

Thus, rather than consider a given response to an attention probe to be a "trial", we used these responses to identify relatively large portions of the full time-series in which we assessed the percentage of time spent in above-threshold oscillatory activity. In addition, as the primary concern with the number of trials in EEG/ERP experiments stems from low signal-to-noise ratios on individual trials (see Boudewyn et al., 2017b), here the entire time-series was subjected to power and duration thresholds prior to extracting individual pre-probe periods for analysis. In other words, only data-points that exceeded the power and threshold criteria with respect to the full dataset went into the calculation of the percentage of above-threshold alpha for a given pre-probe period. We included participants with as few as two instances of an attention probe category or comprehension question response, as this afforded 2500 thresholded data-points from which to calculate the percentage of above-threshold alpha activity. This enabled us to maximize our sample size by avoiding exclusion of participants who lapsed relatively infrequently. We are therefore confident that our design was adequately powered to test our hypotheses of interest, allowing us to connect changes in alpha and attention to language comprehension performance.

4. Results

4.1. *Behavior*

Descriptive behavioral data for attention probes and multiple choice comprehension questions is displayed in Fig. 1.

4.1.1. *Comprehension success as a function of attention*

We analyzed the Incorrect-Guess Rate and No-Idea Rate as a function of Attention Probe in separate repeated measures ANOVA, with Attention Probe response as a within-participants factor (3 levels). The Greenhouse-Geisser correction was applied to all analyses in the paper where appropriate. The Incorrect-Guess Rate did not significantly vary by Attention Probe Response ($F(2,66) = 1.766$; $p = 0.18$), but the No-Idea Rate did ($F(2,66) = 6.711$; $p = 0.004$). Follow-up comparisons showed that the No-Idea Rate was significantly lower for content that preceded On Task responses compared to either Zoned Out responses

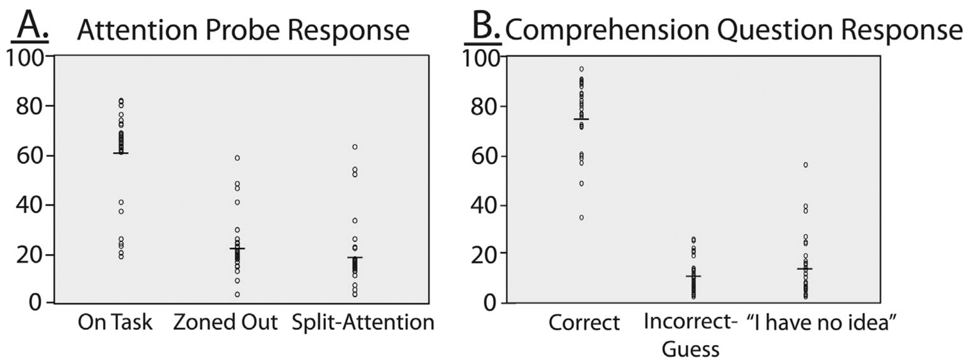

Fig. 1. Panel A: attention probe response data. On average, participants responded that they were On Task 59.8% of the time, Zoned Out 21.9% of the time, and in a Split-Attention state 18.3% of the time. Panel B: Comprehension question response data. On average, participants made a Correct response 75.87% of the time, an Incorrect-Guess 10.74% of the time, and responded that they had No Idea 13.39% of the time. Open circles indicate individual participant averages; dashes denote response category means.

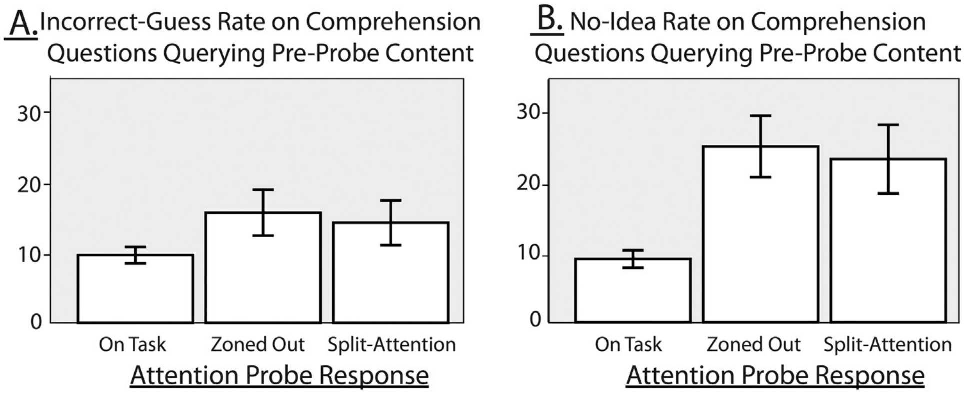

Fig. 2. Panel A: Incorrect-Guess rate on comprehension questions querying content presented just before attention probes, by attention probe response. Panel B: No-Idea rate on comprehension questions querying content presented just before attention probes, by attention probe response. Error bars indicate standard error.

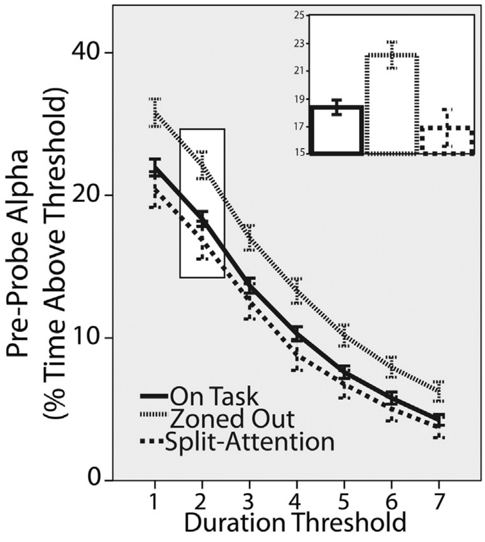

Fig. 3. Percentage of the pre-probe period in which above-threshold alpha-band oscillations were detected, as a function of Attention Probe Response and duration threshold (number of cycles used to define an oscillatory event. Inset displays the 2-cycle duration data in bar plot form. Error bars indicate standard error.

($p = 0.001$) or Split-Attention responses ($p = 0.003$) on the attention probes. This data is displayed in Fig. 2.

4.2. EEG

As described above, the percentage of the pre-probe period in which above-threshold alpha oscillations were detected was calculated for each electrode; the average across 5 log-spaced frequencies from 8 to 12 Hz was used as our alpha measure. Below, we report our analyses examining alpha oscillations as a function of attention probe response and of comprehension question response on the multiple choice questions that followed the story listening task.

4.3. Alpha oscillations as a function of attentional state

We analyzed pre-probe alpha as a function of Attention Probe in a repeated measures ANOVA, with Attention Probe response as a within-participants factor (3 levels). Our initial analyses focused on electrode Cz, a central electrode for which our alpha-band attention effects were maximal in previous studies (Boudewyn et al., 2017a, 2015). We also included a within-participants factor of Duration Threshold (7 levels); this refers to the number of cycles used to define what is considered an oscillatory event (i.e. the duration of the oscillation). We computed estimates of pre-probe alpha activity based on 1, 2, 3, 4, 5, 6 and 7 cycle duration thresholds, as we did not have an *a priori* hypothesis about the most appropriate value to select for this user-defined threshold criterion. There was a main effect of Attention Probe response on oscillatory activity in the alpha band ($F(2,66) = 7.857$; $p = 0.002$), as well as a main effect of Duration Threshold ($F(2,66) = 1175.051$; $p < 0.0001$). There was also a significant interaction of Attention Probe Response by Duration Threshold ($F(12, 396) = 3.4$; $p = 0.02$), reflecting the slightly smaller effects found for higher Duration Thresholds, although it should be noted that the choice of duration threshold did not change the pattern of results. This data is displayed in Fig. 3.

To follow-up on the significant effect of Attention Probe Response, and for all other analyses reported below, we focused on alpha-band oscillations defined using a 2-cycle duration threshold. Follow-up comparisons showed that the percentage of pre-probe alpha was greater for Zoned Out responses compared to either On Task responses ($p = 0.001$) or Split-Attention responses ($p = 0.001$) to the attention

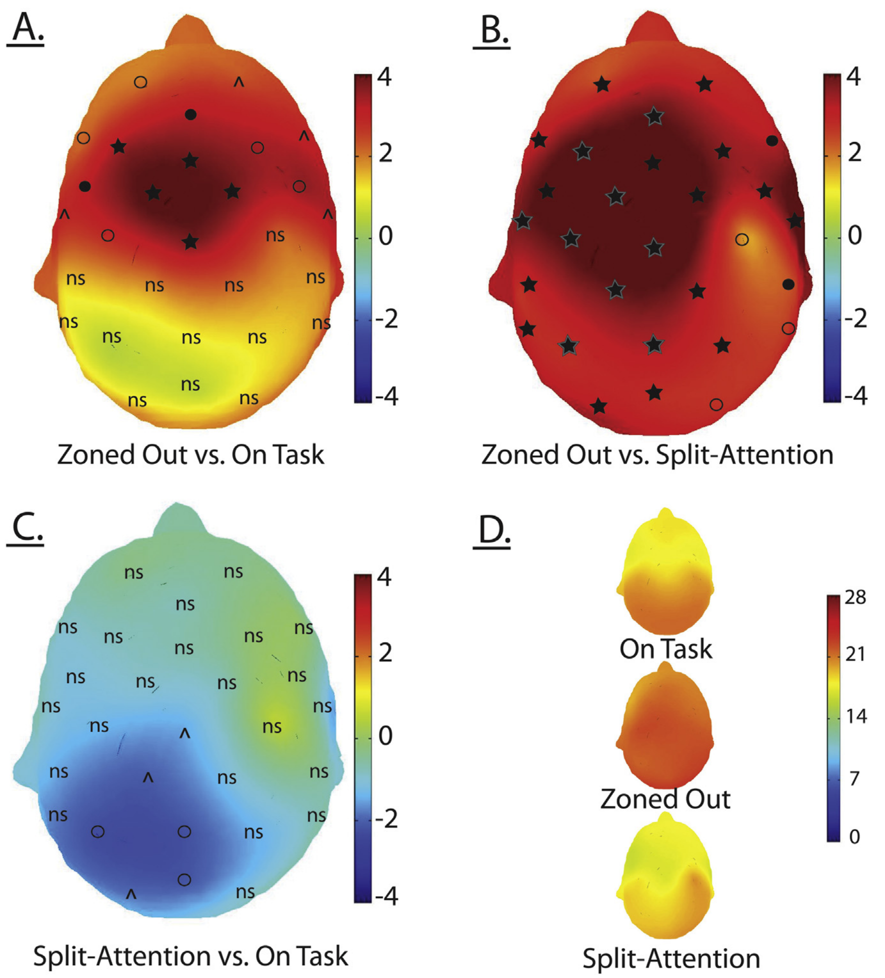

Fig. 4. Topographic distribution of pre-probe alpha as a function of attentional state (% time above threshold). Panel A: Zoned Out minus On Task. Panel B: Zoned Out minus Split-Attention. Panel C: Split-Attention minus On Task. Panel D: Single condition averages. Solid markers indicate electrodes for which the effect remained significant following correction for multiple comparisons (★: $p < 0.001$; ★: $p < 0.01$; •: $p < 0.05$), and open markers indicate effects that did not (○: $p < 0.05$; ˆ: $p < 0.1$). *NS* = not significant.

probes.

This pattern was exclusive to alpha-band oscillations: no significant effects of Attention Probe Response were found in either the theta-band (4–7 Hz) ($F(2, 66) = 2.412$; $p = 0.103$) or the beta-band (15–30 Hz) ($F(2, 66) = 0.647$; $p = 0.483$).

Finally, in order to examine the topographic distribution of this effect, we computed scalp-wide follow-up comparisons as reported above for electrode Cz. Fig. 4 shows the statistical results of the simple comparisons (Panel A: Zoned Out vs. On Task; Panel B: Zoned Out vs. Split-Attention; Panel C: Split-Attention vs. On Task), overlaid on the difference in the percentage of pre-probe alpha between each set of conditions; significant effects that survived Bonferroni correction for multiple comparisons (alpha level of 0.0167) are marked. Fig. 4 Panel D shows the topographic distribution of the percentage of pre-probe alpha for the individual conditions.

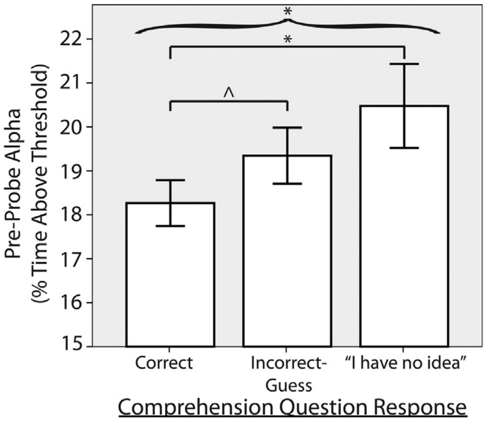

Fig. 5. Percentage of the pre-probe period in which above-threshold alpha-band oscillations were detected, as a function of later response on multiple choice comprehension questions querying pre-probe content. Error bars indicate standard error. $*p < 0.05$, $\hat{}p < 0.1$.

4.3.1. *Alpha oscillations as a function of later comprehension success*

To examine the link between pre-probe alpha oscillations and later behavioral performance on the comprehension questions, we analyzed the percentage of pre-probe alpha as a function of Comprehension Question Response (within-participants factor, 3 levels: Correct, Incorrect-Guess, and No Idea). As above, we initially focused on electrode Cz. There was a significant main effect of Comprehension Question Response ($F(2, 66) = 5.355$; $p = 0.011$). Follow-up comparisons showed significantly less pre-probe oscillatory activity in the alpha-band when questions querying that information were later answered with a Correct response compared to a No Idea Response ($p = 0.012$). The same pattern trended towards significant when comparing Correct to Incorrect Guesses ($p = 0.099$). This data is plotted in Fig. 5.

As above, in order to examine the topographic distribution of this effect, we computed scalp-wide follow-up comparisons as we did for electrode Cz. Fig. 6 shows the statistical results of the simple comparisons (Panel A: Incorrect-guess vs. Correct; Panel B: No Idea vs. Correct; Panel C: No Idea vs. Incorrect-Guess), overlaid on the difference in the percentage of pre-probe alpha between each set of conditions; significant effects that survived Bonferroni correction for multiple

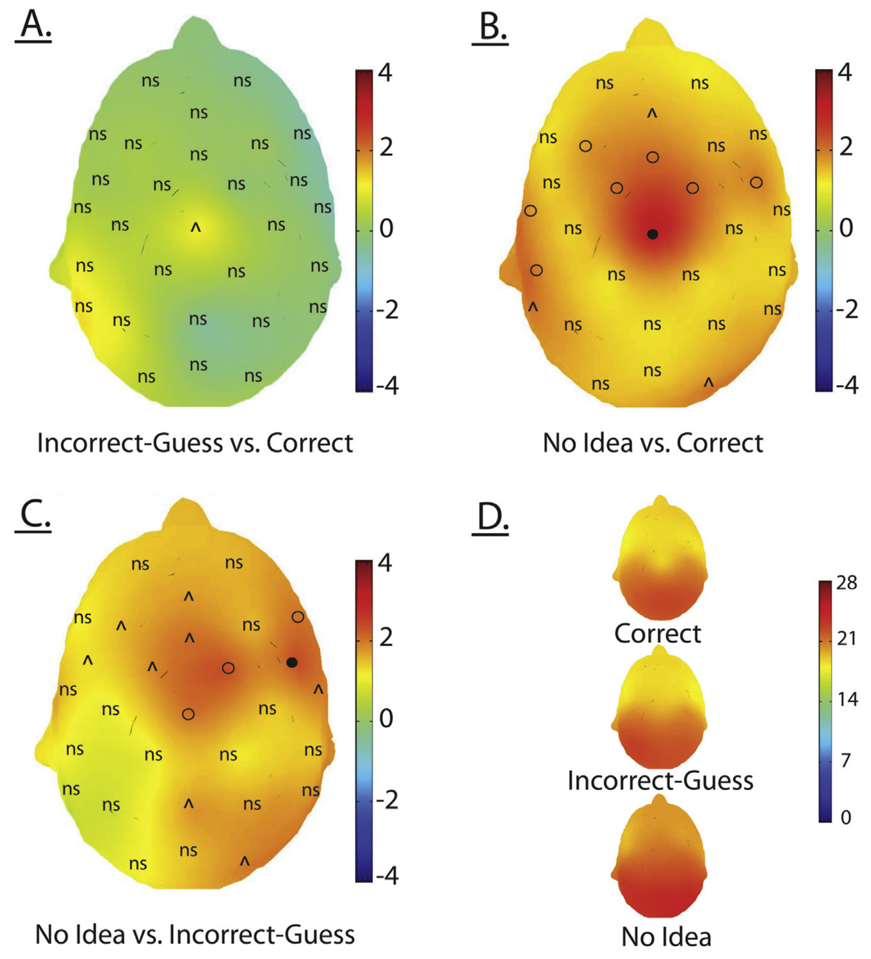

Fig. 6. Topographic distribution of pre-probe alpha as a function of comprehension (% time above threshold). Panel A: Incorrect-Guess minus Correct. Panel B: No Idea minus Correct. Panel C: No Idea minus Incorrect-Guess. Panel D: Single condition averages. Solid markers indicate electrodes for which the effect remained significant following correction for multiple comparisons (★: $p < 0.001$; ★: $p < 0.01$; •: $p < 0.05$), and open markers indicate effects that did not (○: $p < 0.05$; ˆ: $p < 0.1$). *NS* = not significant.

comparisons (alpha level of 0.0167) are marked. Fig. 6 Panel D shows the topographic distribution of the percentage of pre-probe alpha for the individual conditions.

5. Discussion

The goal of this study was to investigate the neural signature associated with lapses in attention during language comprehension, and to connect this to behavioral outcome measures of successful comprehension. We observed a significantly greater percentage of pre-probe alpha (8–12 Hz) activity just prior to the endorsement of an attention lapse, compared to the endorsement of on-task attention or a split-attention state. Pre-probe alpha also related to behavioral outcome: when participants made “I have no idea” responses on the post-EEG comprehension questions, an examination of their EEG during the initial presentation of the information that was queried by those questions revealed significantly more alpha activity compared to when they responded correctly.

5.1. Alpha and attention

There is a wealth of previous EEG research showing that when attention is directed towards external stimuli, alpha activity decreases (e.g. Adrian and Matthews, 1934; Berger, 1929; Mazaheri et al., 2010; Pfurtscheller and Aranibar, 1977; among more recent demonstrations such as; Thut et al., 2006). The flip-side of this phenomenon suggests that increases in alpha may serve as an indication that attention is directed *away* from external stimuli. This is in keeping with current theories on the functional significance of alpha activity that ascribe it a role in inhibition-related cortical functions (Jensen and Mazaheri, 2010; Klimesch, 2012; Romei et al., 2010; Roux and Uhlhaas, 2014). In support of this conceptualization of scalp-recorded EEG activity in the alpha band, a growing number of studies have linked increases in alpha activity to shifting attention away from a stimulus (e.g. Thut et al., 2006), and increases in pre-stimulus alpha to poor performance in response to that stimulus (Boudewyn and Carter, 2017; Boudewyn et al., 2017a, 2015; Erickson et al., 2016). This motivates the use of alpha as a tool to track the general locus of attention (inward vs. outward)[1] during a cognitive task, as we did in the current study. Our results support the idea that decreased alpha is a marker of the engagement of attention to an incoming stimulus, in this case, to spoken language. Our data demonstrates that the link between fluctuations in alpha oscillations and the processing of external stimuli extends to the domain of spoken language. This extends this functional explanation for alpha oscillations to naturalistic spoken story comprehension, a high-order function that engages a large neural network distinct from the visual perception/attention network.

In the current study, the alpha-band results were relatively broadly distributed over the scalp, with a central maximum for the effects of interest (condition comparisons). This is consistent with our previous work investigating alpha during auditory language comprehension processing (Boudewyn et al., 2017a, 2015) as well as with other studies

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[1] It is worth noting that in the mind-wandering literature, this toggling between periods of internally-focused thought and externally-driven processing might be referred to as perceptual decoupling/coupling (see Smallwood, 2013). Perceptual decoupling is hypothesized to aid in separating internal thoughts from external input, and as noted in the introduction, there is some electrophysiological evidence that perceptual processing is indeed attenuated during episodes of mind-wandering (e.g. Baird et al., 2014).

that have connected changes in alpha oscillations to shifts in attention towards/away from auditory stimuli (Strauß et al., 2014; Weisz et al., 2011; Wilsch and Obleser, 2016; Wöstmann et al., 2015). Topographies for individual probe response conditions showed a broad but posteriorly maximal distribution, consistent with the typical distribution of alpha activity observed in studies of visual attention and perception (e.g. Thut et al., 2006). Some studies have linked changes in the topographic distribution of alpha activity to the differential engagement or inhibition of underlying neural circuits (Bengson et al., 2012; Foxe et al., 1998; Fu et al., 2001; Klimesch et al., 1997; Thut et al., 2006). For example, decreases in alpha power have been observed at posterior electrode sites contralateral to to-be-attended locations in a visuospatial attention task, whereas increases in alpha power have been observed at posterior sites contralateral to to-be-ignored locations (Thut et al., 2006). A similar lateralization of alpha power corresponding to shifts of attention has also been found in studies of auditory attention (Wöstmann et al., 2017, 2016). The relatively broad topographic distribution we observed in the current study is consistent with what might be expected given the differences in underlying neural circuitry involved in spoken language comprehension as compared to visual perception.

5.2. *Alpha, attention and comprehension*

Our results demonstrate that changes in oscillatory activity in the alpha band during comprehension do indeed map on to self-reported episodes of mind-wandering, and perhaps more importantly, to poor behavioral outcome. This is a significant advance beyond the results of our previous work in which we linked increased alpha power during key portions of story context with reduced context-dependent ERP effects in a listening task (Boudewyn et al., 2017a, 2015). In those studies, we inferred that the relative increases in alpha power may have reflected lapses of attention to the external task, during which time participants missed the key information, which would explain the reduced context-dependent ERP effects downstream in the story from when the alpha was measured. In other words, in previous studies we were unable to confirm that the alpha effects truly corresponded to momentary lapses in attention from the task, as we had no independent measure of participants' attention to the task. In the current study, we used a novel naturalistic story comprehension paradigm that included attention probes to address this question, and were thus able to quantify the percentage of time participants paid attention to the task, as well as identify specific moments during story comprehension when participants' attention drifted off-task. This enabled us, for the first time, to identify specific pieces of information that were likely to have been missed by the listener due to inattention, and to tie this directly to comprehension performance on a multiple choice test presented after the comprehension task and EEG recording was complete.

A major challenge in studying attention lapses is that off-task thought covers a broad and highly variable range of attentional foci. The design of the current study allowed us to separate out true lapses during which attention was inadvertently directed inward and away from the task (Zoned Out), as opposed to split attention states during which attention was still partially devoted to the task (Split-Attention). This proved critical to characterizing the link between alpha-band oscillations and attention lapses. This is because, as noted above, pre-probe alpha was specifically modulated by whether attention was directed to an external stimulus, even if not fully. Thus, instances in which attention was divided between the external stimulus (the story) and something else (e.g. an unrelated train of thought) still represented periods of time in which attention was at least partially devoted to listening to the story, by definition, and these were characterized by decreased alpha activity relative to periods of time in which attention had drifted away from the external stimulus. However, while comprehension performance was worst (highest "No Idea" response rate) for information that was presented during an attention lapse, comprehension for information that was presented when attention was divided also suffered compared to on-task performance. We highlight this in order to (1) illustrate how, while alpha might provide a means of tracking "zone out" periods, it is ultimately sensitive to the external/internal thought distinction rather than the on-task/off-task distinction; and (2) make it clear that we do not wish to suggest that full attention lapses are the only predictors of poor comprehension performance, as comprehension also suffered from periods of split-attention. Rather, lapses of attention represent one of many potential reasons that an individual might fail to recall a piece of information.

Finally, another question that arose out of our previous studies concerned how fluctuations in alpha and attention during language processing ultimately connect to comprehension. In the current study, we used a full-length spoken story listening task followed by multiple-choice comprehension questions in order to be able to address this question. The inclusion of an "I have no idea" response on the multiple choice comprehension questions afforded us a measure of information that was truly "missed" during lapses in attention to the stories when alpha activity was particularly high. This result has relevance not just for ideas about alpha activity in scalp-recorded EEG and its relation to attention, but for language comprehension more generally. Studies of language processing often assume that individuals are paying attention to the task, even though, as our results highlight, a substantial portion of information is missed due to periods of inattention to the task. This was the case despite our full-length detective stories being relatively engaging as compared to expository text (Dixey and Baird, 1996; Ross, 1994) or to the short, unrelated sentences or passages often used in most psycholinguistic experiments (including our own) (Mitchell, 1984). It may therefore be the case that the rate of attention lapses and resulting poor performance due to inattention that we observed in the current study is actually a conservative estimate of the impact of lapsing during comprehension. If so, lapses of attention in typical laboratory or educational settings could account for an even greater amount of variance in comprehension than reported here. The extent to which lapses in attention account for performance on different types of comprehension tasks (e.g. narrative text vs expository text) would be an interesting question to investigate in future studies.

6. Conclusions

The results of the current study demonstrate how oscillatory activity in the alpha-band can be used as a tool to track attentional engagement during listening comprehension. Further, we were able to map alpha activity and participant-reported lapses of attention to behavioral measures of comprehension outcome. These results illustrate the dependence of successful comprehension on attention, and provide insight into the neural signature of momentary lapses in attention during language comprehension.

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