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

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ABSTRACT

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