Does closing the eyes enhance auditory attention?
Eye closure increases attentional alpha-power modulation but not listening performance

Running title: Eye closure and auditory attention

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Abstract

In challenging listening conditions, closing the eyes is a strategy with intuitive appeal to improve auditory attention and perception. On the neural level, closing the eyes increases the power of alpha oscillations (~10 Hz), which are a prime signature of auditory attention. Here, we test whether eye closure benefits neural and behavioural signatures of auditory attention and perception. Participants (*N* = 22) attended to one of two alternating streams of spoken numbers with open or closed eyes in a darkened chamber. After each trial, participants indicated whether probes had been among the to-be-attended or to-be-ignored numbers. In the electroencephalogram, alpha power was modulated in synchrony with auditory attending versus ignoring. Importantly, eye closure did not only increase the overall level of absolute alpha power but also the attentional modulation thereof. Behaviourally, however, neither perceptual sensitivity nor response criterion was affected by eye closure. To further examine whether this behavioural null-result would conceptually replicate in a simple auditory detection task, a follow-up experiment was conducted that required participants (*N* = 19) to detect a near-threshold target tone in noise. As in the main experiment, our results provide evidence for the absence of any difference in perceptual sensitivity and criterion for open versus closed eyes. In sum, we demonstrate here that the modulation of the human alpha rhythm by auditory attention is increased when participants close their eyes. However, our results speak against the widely held belief that eye closure per se improves listening behaviour.

When we listen to faint sounds in noise-contaminated environments, we sometimes close our eyes with the intention to strengthen the focus on auditory sensory input. In theory, eye closure has been proposed to free perceptual and cognitive resources (Glenberg et al., 1998; Vredeveldt et al., 2011) to focus attention on non-visual sensory information. But does eye closure indeed have the potency to enhance auditory attention and perception?

There is some evidence that closing the eyes can improve performance in certain sensory and cognitive tasks. Somatosensory perception thresholds decrease when participants have their eyes closed compared to open, in an illuminated but even in a dark room (Brodoehl et al., 2015b; Brodoehl et al., 2015a). This speaks to the general potency of eye closure to enhance perceptual processing. Evidence for enhanced cognitive capacity through eye closure comes from studies showing that eyewitnesses' recall of the details of a crime scene improves when they close their eyes during memory recall (e.g., Perfect et al., 2008; Vredeveldt et al., 2012; Vredeveldt et al., 2015). However, systematic investigations of the impact of eye closure on perceptual and cognitive functions across sensory modalities are sparse at best.

Evidence for listeners' use of eye closure as a strategy to improve listening is mostly anecdotal. In his seminal paper establishing the Cocktail party effect, Colin Cherry (1953) studied listeners' separation of two concurrent spoken messages and noted that "At the subjective level the subject reported great difficulty in accomplishing his task. He would shut his eyes to assist concentration."[1] Nowadays, it is common practice in auditory research to put efforts into avoiding that participants close their eyes in the laboratory. It is all the more surprising that there is to our knowledge no published work on the behavioural or neural consequences of closing the eyes during attentive listening (but see Götz et al., 2017 for initial evidence from a combined somatosensory and auditory study).

Indirect evidence in favour of an eye–closure-induced modulation of auditory processing comes from studies showing that eye closure in darkness increases the blood oxygen level dependent (BOLD) contrast in auditory cortex regions (Marx et al., 2003; Marx et al., 2004) and increases the acoustic reflex (Corcoran et al., 1980), that is, a sound-induced muscle contraction in the middle ear. Furthermore, eye position has been shown to impact activity in inferior colliculus (Groh et al., 2001) and auditory cortex (Werner-Reiss et al., 2003) in

[1] Cherry CE (1953) Some Experiments on the Recognition of Speech, with One and with Two Ears. Journal of the Acoustical Society of America 25:975-979. P. 976

primates. The present study aims at testing whether eye closure affects one of the arguably most abundant listening situations in everyday life, that is, listening to an auditory signal despite distraction.

Neuroscience has actually long established an indirect link between eye closure and auditory attention: It is known since the work by Hans Berger and Lord Adrian in the 1940s that eye closure and auditory attention induce a similar electrophysiological response: an increase in the power of alpha oscillations (~10 Hz) at parietal and occipital scalp sites (Berger, 1929; Adrian and Matthews, 1934; Adrian, 1944). More recently, high alpha power has been interpreted as a means to relatively inhibit neural processing in task-irrelevant brain areas (Jensen and Mazaheri, 2010; Foxe and Snyder, 2011). Among other cognitive processes that modulate the power of alpha oscillations, auditory tasks increase alpha power in parieto-occipital cortex regions, possibly in order to increase attention to the auditory modality (e.g., Fu et al., 2001; Weisz et al., 2011; Strauß et al., 2014).

Alpha power modulations do covary with behavioural performance in auditory attention and memory paradigms (e.g., Wilsch et al., 2015; Wöstmann et al., 2015b; Wöstmann et al., 2016a). Furthermore, we have recently shown that modulatory brain stimulation at alpha frequencies influences the degree of distraction by irrelevant speech (Wöstmann et al., 2018). It is thus likely that alpha power is of functional relevance to auditory attention. The rationale of the present study is the following: If the eye–closure-enhanced alpha oscillators in parieto-occipital cortex regions (partly) overlap with the alpha oscillators active during auditory attention, then closing the eyes should increase the auditory attention-induced modulation of alpha power. Beyond effects on neural oscillatory dynamics, we here tests whether eye closure also has the potency to improve behavioural performance in auditory attention and perception.

In the main experiment, participants (N = 22) selectively attended to one of two alternating streams of spoken numbers. We operationalized successful auditory attention as the difference in neural and behavioural responses to to-be-attended versus to-be-ignored speech segments. To rule out that effects of eye closure were due to the simple blocking of the task-irrelevant visual scenery, participants performed the task in a darkened chamber, with eyes open or closed during half of the blocks of the experiment. In a follow-up experiment, we tested the impact of eye closure on the detection of non-speech stimuli in noise in a separate sample of participants (N = 19).

Materials and Methods

Participants. Healthy, right-handed, native German-speaking participants took part in the main experiment (*N* = 22; 12 females; age range 19–31 years, *M* = 24.68, *SD* = 3.06) and in the follow-up experiment (*N* = 19; 17 females; age range 20–31 years, *M* = 23.89, *SD* = 4.04). In the main experiment, the data of one additional participant were excluded from all analyses due to noise-contaminated EEG signals. All participants signed informed consent and were financially compensated for participation. All procedures were approved by the local ethics committee of the University of Lübeck.

Auditory materials in the main experiment. Speech stimuli consisted of two sets of 72 spoken numbers from 21 to 99 excluding integer multiples of 10. One set was spoken by a trained German female speaker (used in previous studies; Wöstmann et al., 2015b; Wöstmann et al., 2015a) and the other by a male speaker. For instructions, a third set of numbers and spoken instructions was recorded from a different German female speaker. Praat software (version 6.0.18) was used to shift the formant frequencies of this third speaker slightly towards a male voice (formant shift ratio of 1.3), in order to render the instructor voice gender-neutral. Speech recordings were made in a soundproof room and digitized at a sampling rate of 44.1 kHz. Numbers ranged in duration from 1.01 to 1.26 s (*M* = 1.12, *SD* = 0.06) and comprised four syllables.

For each trial, five randomly selected female-voiced numbers and five randomly selected male-voiced numbers were alternately assigned within the ten-number sequence. Half of the trials started with a female-voiced number, that is, all odd number positions were occupied by female-voiced numbers and all even number positions by male-voiced numbers (and vice versa for trials starting with a male-voiced number). All ten numbers in a trial were different from and numerally non-successive to one another. The time interval between the onsets of two sequent numbers was 1.33 s. Number sequences were energetically masked by continuous white noise (signal-to-noise-ratio of +10 dB) with onset and offset raised cosine ramps of 0.15 s preceding and ensuing a number sequence, respectively. Number sequences in background noise ranged in duration from 13.28 to 13.53 s (*M* = 13.39, *SD* = 0.06) depending on the duration of the last number.

Procedure of the main experiment. The experiment was designed in a way that it could be performed with open but also with closed eyes. Each trial started with the spoken instruction to attend to the female- or male-voiced numbers. After 0.9 s (randomly jittered 0.6–1.2 s), a sequence of ten numbers was presented. Another 0.9 s (randomly jittered 0.6–

1.2 s) after number sequence offset, three probe numbers of this trial were uttered by the instructor voice. After each probe, participants responded via button press on a computer mouse whether the probe was one of the to-be attended numbers (left button, 'Yes, attended'-response) or not (right button, 'No, ignored'-response). There was no time limit for a response (Fig. 1A).

Numbers from the temporally middle positions were probed more frequently. In detail, for each condition in the 2 (Eyes: open vs. closed) × 2 (Attended voice: male vs. female) × 2 (Attended positions: odd, stream A vs. even, stream B) design, 60 to-be-probed number positions (for 20 trials with three probes each) were predefined: Number positions 1, 2, 9, and 10 were probed three times each; number positions 3, 4, 7, and 8 were probed seven times each; and number positions 5 and 6 were probed ten times each.

During the whole trial a grey fixation circle was presented in the middle of a black computer screen placed in front of participants. Trials were separated by a time interval of 1.3 s. All ten numbers presented in a trial were excluded from reoccurring in the subsequent trial.

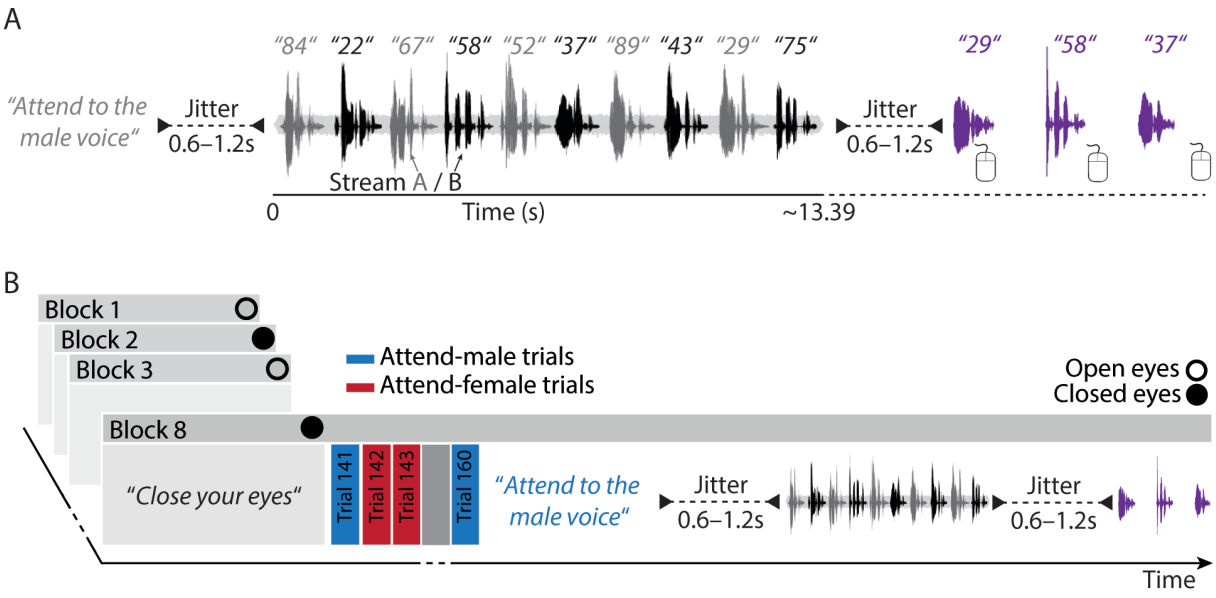

Figure 1. Task design of the main experiment. (A) In each trial, listeners attended to speech stream A (grey numbers) or B (black numbers), each composed of five spoken German numbers embedded in a white noise masker (+10 dB SNR). At the end of each trial, three probe numbers were presented (purple). Participants had the task to indicate with a mouse button press, whether the probed number was 'attended' or 'ignored'. (B) Each one of eight blocks started with the instruction to keep the eyes open or closed during the entire block. For each trial within a block, the task instruction to attend to the male or female voice was randomly assigned.

Twenty trials of the experiment formed a block; a total of 8 blocks resulted in 160 trials per participant. At the beginning of a block participants were presented a spoken instruction to either close their eyes or to keep them open. Blocks were alternately worked through with open and closed eyes, whereby half of the participants completed the first block with open eyes. The entire experiment was performed in a darkened chamber. The light was turned on in between blocks for a self-paced break of at least one minute.

Stimulation was controlled by Presentation software (version 18.3; Neurobehavioural Systems). Auditory stimuli were presented via headphones (Sennheiser HD 25-1 II). During the whole procedure participants were monitored via infrared camera to ensure they consistently kept their eyes open or closed in agreement with the instruction. The experiment took approximately 75 minutes to complete (i.e., ~8 minutes per block).

Auditory materials in the follow-up experiment. The target tone was a 1000-Hz sine tone of 100-ms duration and 10-ms linear onset and offset ramps. The distracting background noise was bandpass-filtered random noise (500–1500 Hz) of 3-s duration and 50-ms linear onset and offset ramps. For each trial of the follow-up experiment, a different background noise stimulus was created.

Procedure of the follow-up experiment. As the main experiment, the follow-up experiment was designed in a way that it could be performed with open but also with closed eyes. Participants had the task to report detection of the target tone in noise using a computer mouse (left button: 'Yes', tone detected; right button: 'No', no tone detected). The target tone was present on 50% of trials. For target-present trials, the onset of the target tone was placed at a random millisecond-value between 1500 and 2100 ms following background noise onset. The experiment contained 600 trials, divided in 12 blocks à 50 trials (25 target-present trials and 25 target-absent trials). Every other block was performed with closed versus open eyes, with participants with odd versus even experiment-IDs starting with open versus closed eyes, respectively. Pre-recorded instructions in the beginning of each block ("Keep your eyes open/closed") and in the end of each block ("This block is finished, take a brief break") were spoken by a male voice. All auditory stimuli were delivered via headphones (Sennheiser HD 25-1 II). The follow-up experiment took approximately 75 minutes to complete. The experiment was performed in a darkened chamber, with the computer monitor switched off for the entire duration of the experiment. As in the main experiment, participants were monitored via infrared camera to ensure they consistently

kept their eyes open or closed in agreement with the instruction. The light was switched on in the breaks in-between blocks of the experiment.

Prior to the start of the follow-up experiment, we titrated the Signal-to-Noise Ratio (SNR) of the target tone in noise for each individual participant with eyes open and the light switched on. To this end, participants performed a one-up one-down staircase procedure to determine the SNR for a proportion correct of 0.5 for target-present trials. Note that a proportion correct of 0.5 for target-present trials is typically accompanied by a somewhat higher proportion correct for target-absent trials (see Fig. 5E). Subsequently, participants performed a training block including 50 trials (25 target-present trials). The main experiment started if proportion correct averaged across target-present and target-absent trials was close to 0.65 (between 0.55 and 0.75). Otherwise, the SNR was adjusted and the training block was repeated.

Behavioural data analysis. In the main experiment, in order to base behavioural and EEG analyses on the same data, we only considered trials that passed the artefact rejection of EEG data (see below) for the behavioural data analysis.

On each trial, participants made three behavioural responses to judge the probes either as 'Yes, attended' or 'No, ignored'. We calculated the proportions of Hits (correct 'Yes, attended'-responses for to-be-attended probes), Misses (incorrect 'No, ignored'-responses for to-be-attended probes), Correct rejections (correct 'No, ignored'-responses for to-be-ignored probes), and False alarms (incorrect 'Yes, attended'-responses for to-be-ignored probes). Sensitivity (d') and response bias (c) were calculated according to signal detection theory (Macmillan and Creelman, 2005; Formulas 1.5 and 2.1, respectively), separately for eyes open versus closed conditions. Larger values of d' indicate higher sensitivity in internally separating attended from ignored numbers. Larger positive values of c indicate more conservative bias to respond 'No, ignored' more often.

In the follow-up experiment, we calculated the proportions of Hits (correct 'Yes'-responses in target-present trials), Misses (incorrect 'No'-responses in target-present trials), Correct rejections (correct 'No'-responses in target-absent trials), and False alarms (incorrect 'Yes'-responses in target-absent trials), separately for trials with open versus closed eyes. As for the main experiment, proportions of Hits and False alarms were used to obtain sensitivity (d') and response bias (c).

EEG recording and preprocessing. In the main experiment, participants were seated in an electrically shielded sound-attenuated EEG chamber. While they were prepared for EEG

recordings, they performed a feedback-based training session (10 trials) with eyes open and lights on to get used to the task.

The electroencephalogram (EEG) was recorded at a sampling rate of 1 kHz with a pass-band from direct current (DC) to 280 Hz (actiCHamp, Brain Products). Sixty-four Ag/AgCl electrodes were fixed to an elastic cap (actiCAP) according to the extended 10-20 standard system at the following positions: FP1/2, AF3/4/7/8, F1–8, FC1–6, FT7–10, C1–6, T7/8, CP1–6, TP7–10, P1–8, PO3/4/7/8, O1/2, FPz, AFz, Fz, FCz, Cz, CPz, Pz, POz, and Oz. The ground electrode was mounted on the forehead (FPz). During recording, electrodes were referenced against the left mastoid (TP9) and all impedances were kept below 5 kΩ.

EEG data were preprocessed and analysed using Matlab (version R2013b, MathWorks) and the FieldTrip toolbox (version 2012-12-16; Oostenveld et al., 2011). From the continuous data, epochs were extracted time-locked to the onset of acoustic stimulation in each trial (–1 to 14 s). Due to technical problems during recording, there were missing 1, 4, or 20 epochs out of 160 for three participants. Epochs were high-pass filtered at 1 Hz and low-pass filtered at 100 Hz using 6th order Butterworth filters.

For three participants, signals of bad EEG electrodes were interpolated. A bad electrode was defined as an electrode whose impedance was >5 kΩ at the end of the preparation for EEG measurements. The signal at electrode AF (one participant) and F6 (two participants) was replaced by a weighted average signal of neighbouring electrodes using the nearest-neighbours method.

An independent component analysis (ICA) was performed on each participant's entire dataset (including eyes open and eyes closed conditions). Components' time courses, topographies, and frequency spectra were inspected for artefacts (i.e., eye blinks, saccades, cardiac activity, and other muscle activity). On average, 50.48% of components (*SD* = 11.22) were removed from the data. Further, single epochs were removed from the data if any channel's activity range was greater than 250 μV within the time interval of the number stream in noise (0 to 13.53 s). On average 1.8% of epochs (*SD* = 2.64) were excluded from further analyses. All epochs were re-referenced to the average of all electrodes.

In the follow-up experiment, the EEG was recorded but not analysed for the purpose of the present study.

Analysis of oscillatory power. We performed two spectral analyses. First, non-time-resolved absolute oscillatory power across the average trial duration (0–13.39 s) was obtained using Fast Fourier Transform (FFT) with multitapering for frequencies 0.5–20 Hz in

steps of 0.5 Hz with 1 Hz spectral smoothing, separately for trials with open versus closed eyes (Fig. 2A). Source localization of absolute alpha power (8–12 Hz) was performed using the Dynamic Imaging of Coherent Sources (DICS) beamformer approach (Gross et al., 2001). A standard headmodel (Boundary Element Method, BEM; 3-shell) was used to calculate leadfields for a grid of 1 cm resolution. For each participant, we calculated an adaptive spatial filter from the leadfield and the cross-spectral density of Fourier transforms of all trials (eyes open and closed) centered at 10 Hz with ±2 Hz spectral smoothing (resulting in a frequency range of 8–12 Hz) in the time interval 0–13.39 s relative to sound onset. This filter was applied separately to single-trial Fourier transforms of eyes open and closed conditions to obtain alpha power at each grip point (Fig. 2B).

Second, time-resolved power was obtained for four experimental conditions in the 2 (Eyes: open vs. closed) × 2 (Attended stream: A, odd positions vs. B, even position) design. Since we did not expect neural differences of attention to female- vs. male-voiced numbers, we collapsed across the two levels of the factor Attended voice (female vs. male) for all further analyses. Oscillatory power was obtained via calculation of complex Fourier coefficients for a moving time window (fixed length of 0.5 s; Hann taper; moving in steps of 0.02 s through the trial). Power (squared magnitude of complex Fourier coefficients) was obtained for frequencies 1–20 Hz with a frequency resolution of 0.5 Hz.

In order to descriptively characterize time courses of alpha power for open and closed eyes (irrespective of whether participants attended to stream A or B), we fitted a power function ($y = a * (t^m) + intc$, with t = time, a = scaling parameter, m = exponential coefficient, and intc = intercept) to individual participants' 8–12 Hz power time courses in the time interval –0.7–13.39 s relative to sound onset (using the *powerfit* function and the least squares procedure implemented in the *lsqcurvefit* function in Matlab).

For all analyses of the attentional modulation of oscillatory power, to remove possible influences of absolute power, single–subject time-frequency representations were averaged across trials and baseline-corrected by subtraction of average power throughout the entire trial (0–13.39 s). To quantify the influence of attention on oscillatory power, we obtained a measure of attentional modulation (Fig. 3B) through subtraction of time-frequency spectra for attention to stream A minus attention to stream B, separately for open versus closed eyes for each participant. To quantify the strength to which attention rhythmically modulated oscillatory power, we calculated Fourier spectra on single subject's power time-courses (0–13.39 s) obtained from the attentional modulation (Wöstmann et al.,

2016a). Plotting the amplitudes of Fourier spectra against EEG frequencies revealed modulation spectra (Fig. 3C).

For statistical analysis, single-subject modulation spectra for closed versus open eyes were contrasted using a cluster permutation dependent-samples t-test (Maris and Oostenveld, 2007). This test clusters adjacent bins of modulation spectra and compares the summed t-statistic of the observed cluster against 1000 randomly drawn clusters from the same data with permuted condition labels. As hypothesized, the test revealed one significant positive cluster (closed > open eyes) in the alpha frequency band (~10 Hz) at a modulation frequency of the attention rhythm (0.375 Hz; Fig. 3C). Besides this hypothesized cluster, one additional significant positive cluster was found in the upper alpha band (~10–12 Hz), however for slow modulation frequencies < 0.05 Hz (cluster *p*-value = 0.01; not shown), which did not correspond with the task-induced rhythmic 0.375 Hz progression of attending and ignoring. No significant negative clusters were found (all cluster *p*-values > 0.15).

In order to localize neural sources of the hypothesized significant positive cluster, the Linearly Constrained Minimum Variance (LCMV) beamformer approach was used to construct a common filter (based on all trials in all conditions). This common filter was used to project single-trial EEG time courses into source-space. Next, time-frequency spectra and modulation spectra were calculated for each grid point (in the same way as for single electrodes in sensor space; see above). Finally, z-values for the contrast closed versus open eyes were obtained using non-parametric Wilcoxon signed rank tests for EEG frequency 10 Hz and modulation frequency 0.375 Hz for each grid point (Fig. 3D).

Statistical analyses. We applied parametric *t*-tests when the data conformed to normality assumptions ($p > 0.05$ in Shapiro–Wilk test) and non-parametric Wilcoxon signed rank tests otherwise. For effect sizes, we report $r_{equivalent}$ (Rosenthal, 1994; Rosenthal and Rubin, 2003), which is bound between 0 and 1. For non-significant results of statistical tests, we additionally report the Bayes Factor (*BF*; obtained in JASP). In brief, a $BF > 3$ gives support for the alternative hypothesis (i.e., the data would be considered 3 times more likely to occur under the alternative hypothesis than under the null), whereas a $BF < 0.33$ gives support for the null hypothesis (Jeffreys, 1939).

Results

In the main experiment, we presented participants with two alternating streams of five spoken numbers, each. The leading stream (stream A; grey numbers in Fig. 1A) was distinguishable from the lagging stream (stream B; black numbers in Fig. 1A) by talker gender (female vs. male). Every female-voiced number was thus followed by a male-voiced number and vice versa. On each trial, participants were instructed to attend either to the stream spoken by the female or male voice, which was either the leading or lagging stream. Each participant performed 8 blocks (à 20 trials) in a darkened chamber. Participants kept their eyes open or closed during every second block, respectively.

Closing the eyes shapes dynamics of absolute alpha power. Eye closure affected absolute (i.e., not baseline corrected) alpha power in two ways. First, as expected, 8–12 Hz power across the entire trial time (0–13.39 s) was significantly enhanced for closed compared with open eyes (Fig. 2A; Wilcoxon signed rank test; $z = 3.26$; $p = 0.001$; $r = 0.7$), primarily in occipital cortex regions (Fig. 2B).

Second, and less expected, eye closure also affected the time course of absolute alpha power during a trial (Fig. 2C). For open eyes, alpha power showed the typical moderate increase in the beginning of a listening task (e.g., Wöstmann et al., 2015b; Henry et al., 2017), followed by saturation. For closed eyes, however, alpha power started out much higher and decreased in the beginning of a trial before levelling well above the open-eyes saturation. In order to descriptively trace these alpha power de-/increases, we fitted power functions to individual participants' alpha time courses. Exponential coefficients of fitted power functions were significantly smaller (i.e., negative instead of positive) for closed compared with open eyes (Wilcoxon signed rank test; $z = -2.03$; $p = 0.042$; $r = 0.43$), which shows that eye closure reverses the commonly observed alpha power increase at the onset of an attention-demanding listening task into a power decrease.

Closing the eyes enhances attentional modulation of alpha power. The major hypothesis of this research was not concerned with the absolute level of alpha power but instead with the attentional modulation thereof. As expected, the temporal (0.375-Hz) fluctuation of attending and ignoring speech induced synchronized states of respective high and low alpha power (Fig. 3A) for open and closed eyes. That is, alpha power relatively increased shortly before and initially during the presentation of a to-be-attended number, whereas it relatively decreased later during number presentation and shortly thereafter.

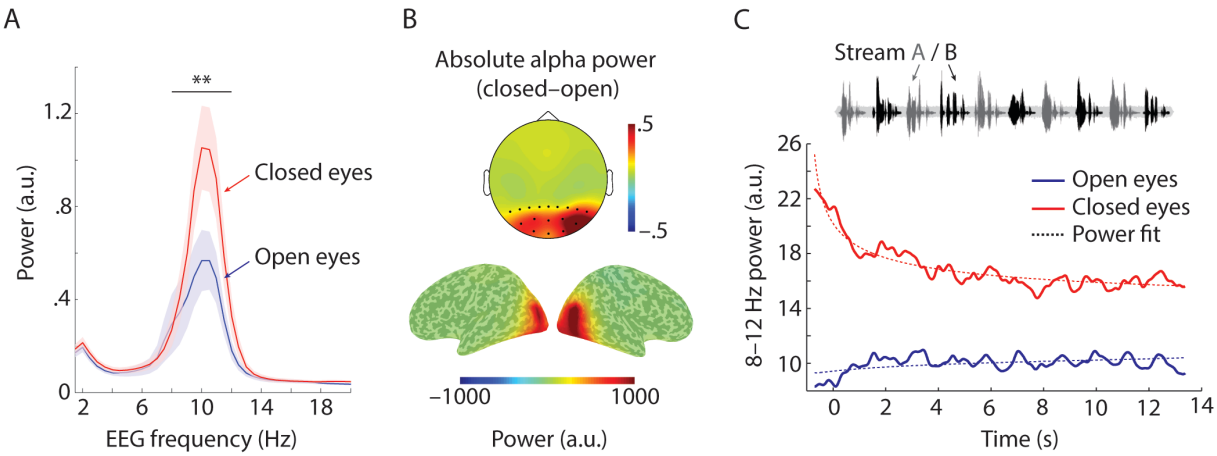

Figure 2. Absolute alpha power in the selective listening task. (A) Average absolute oscillatory power ±1 between-subject SEM during the trial (0–13.39 s; across $N = 22$ participants and occipital electrodes highlighted in topography in B) increased for closed (red) compared to open eyes (blue) in the alpha frequency band (8–12 Hz; ** $p = 0.001$). (B) Activation maps on inflated brain surfaces show the contrast of 8–12 Hz source-localized power for closed–open eyes. (C) Time courses of oscillatory alpha power averaged across 17 electrodes highlighted in B, separately for eyes-open (blue) and eyes-closed trials (red). Dashed lines show the average across individual participants' power function fits to the data.

Since to-be-attended and to-be-ignored numbers were placed at opposing positions in trials where participants attended to stream A versus B, the difference (attend to A–B; Fig. 3B) was used to quantify the neural difference in attending versus ignoring, referred to as 'attentional modulation' hereafter. The strength of the rhythmic attentional modulation of oscillatory power (i.e., an FFT calculated on the attentional modulation) is shown in modulation spectra in Figure 3C. In line with prior research (Wöstmann et al., 2016a), peaks in modulation spectra show that the 10-Hz alpha power envelope reliably tracked the 0.375-Hz temporal progression of attending versus ignoring. Most importantly, a cluster permutation test revealed that the amplitude of rhythmic alpha modulation was stronger with closed compared to open eyes (cluster p-value < 0.001). Beamformer source reconstruction localized the significant increase in 10-Hz power modulation at the attention rhythm of 0.375 Hz under closed eyes mainly in occipital and parietal cortex regions (Fig. 3D).

It is of note that the attentional modulation of 10-Hz power at 0.375 Hz for closed–open eyes correlated with the absolute alpha power increase with closed eyes ($r_{Spearman} = 0.67$; $p < 0.001$). This means that participants with stronger increases in absolute alpha power with closed eyes also exhibited stronger increases in the attentional modulation of alpha power for closed compared to open eyes. In addition to the amplitude of the attentional modulation of alpha power, we also analysed the 0.375-Hz phase angles of the 10-Hz power

modulation, which did, however, not differ for closed versus open eyes (Parametric Hotelling paired-samples test for equal angular means; $F_{40} = 1.02$; $p = 0.38$).

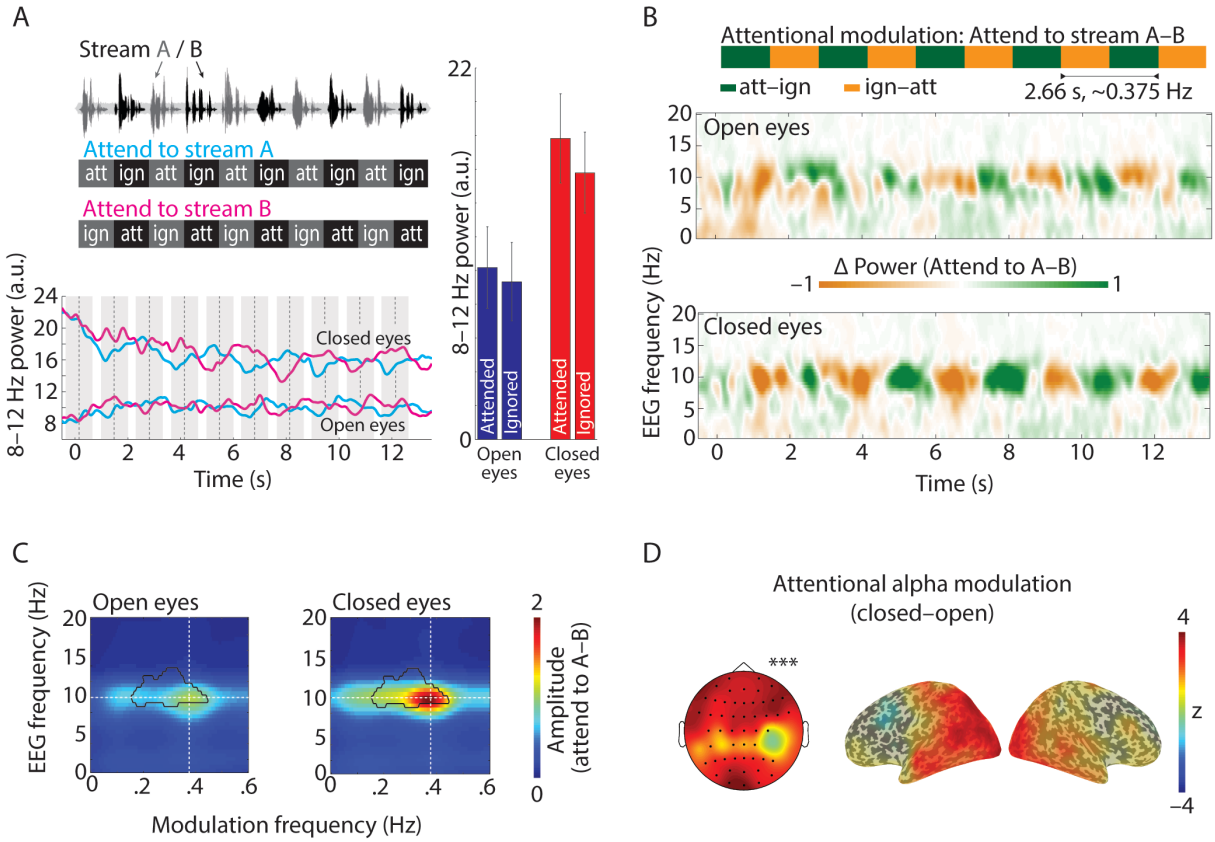

Figure 3. **Closing the eyes enhances neural signatures of auditory attention**. (A, top) Our task design was intended to induce fluctuation between states of attending (att) and ignoring (ign) over the time course of a trial. (A, bottom) Oscillatory alpha power averaged across ($N = 22$) participants and 17 occipito-parietal scalp electrodes (highlighted in Fig. 2B) for trials where participants attended to stream A (cyan) or B (pink) with eyes open (bottom lines) or closed (top lines). Bars and error bars show mean ±1 between-subject SEM of 8–12 Hz alpha power, averaged across occipito-parietal scalp electrodes and time intervals −0.5 to 0.5s around onsets of attended or ignored numbers (grey shaded areas in line plot). (B) Contrasting trials with attention to stream A–B revealed the attentional modulation, which alternated between states of 'att–ign' or 'ign–att' at a rate of 0.375 Hz. Time-frequency spectra show the attentional modulation of grand-average oscillatory power (across $N = 22$ participants and 64 scalp electrodes) for open (top) and closed eyes (bottom). (C) Modulation spectra of the attentional modulation show average amplitudes of Fourier spectra calculated on EEG power envelopes for frequencies 1–20 Hz and modulation frequencies 0–0.6 Hz. Strongest power modulation was observed at the intersection of the alpha band (10 Hz) and the attention rhythm (0.375 Hz, dashed lines). Black outlines show a significant positive cluster (*** $p < 0.001$) for closed vs. open eyes, resulting from a cluster permutation test. (D) Cluster z-values for EEG and modulation frequency (10 Hz and 0.375 Hz, respectively) are shown on topography (significant electrodes of cluster highlighted) and inflated brain surfaces.

Effect of closing the eyes is specific to power, but not phase of neural oscillations. As a control analysis, we tested whether the observed increase in the attentional modulation of neural oscillations with closed eyes was specific to power or whether it would also show up

in the phase-locking across trials (which would speak to evoked, rather than induced power modulation; see Wöstmann et al., 2017). To this end, we performed the very same analysis as shown for power in Figure 3 for inter-trial phase coherence (ITPC; Lachaux et al., 1999).

During a trial of the selective listening, low-frequency (0–8 Hz) ITPC peaked at the onsets of spoken numbers (Fig. 4A). The attentional modulation of ITPC (Fig. 4B&C) did not show any pattern of rhythmic modulation at the frequency of 0.375 Hz. A cluster permutation test on ITPC modulation spectra did not reveal any clusters of significant differences for the contrast closed versus open eyes (all cluster *p*-values > 0.07).

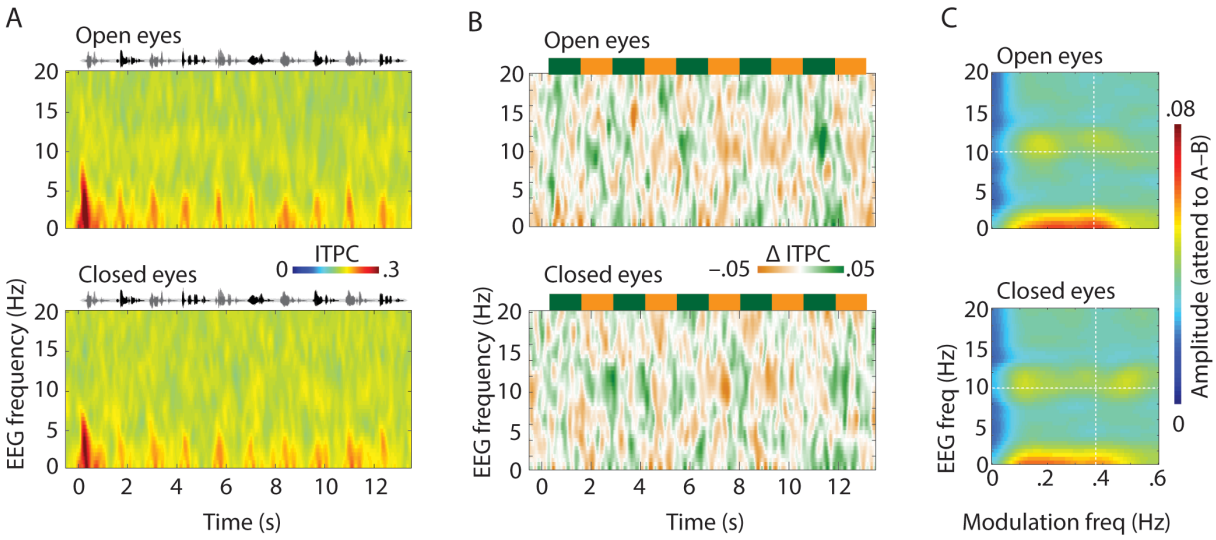

Figure 4. No effect of eye closure on phase-locking of neural oscillations. (A) Average inter-trial phase coherence (ITPC) across *N* = 22 participants and 64 EEG scalp electrodes for trials with eyes open (top) or closed (bottom). (B&C) Same as Fig. 3B&C but for ITPC.

No sizable relation of attentional alpha power modulation and behaviour. At the end of each trial of the main experiment, we presented participants with three random numbers previously presented in that trial (spoken by a gender-neutral voice). Participants indicated for each of these probe numbers, whether it had been among the to-be-attended numbers ('Yes, attended'-response) or not ('No, ignored'-response). We tested whether the attentional modulation of alpha power would relate to behavioural performance.

First, we calculated modulation spectra (see Fig. 3C), separately for correct trials (3 correct responses) and incorrect trials (< 3 correct responses). The attentional modulation of 10-Hz power at 0.375 Hz averaged across 17 occipital electrodes (highlighted in Fig. 2B) was submitted to a 2 (Eyes: open vs. closed) x 2 (Accuracy: correct vs. incorrect) repeated-

measures ANOVA. The ANOVA yielded a weak main effect of Accuracy ($F_{1,21} = 4.17$; $p = 0.054$), indicating a tendency for stronger attentional alpha power modulation for correct compared to incorrect trials. The Eyes x Accuracy interaction was not significant ($F_{1,21} = 0.09$; $p = 0.77$). Note, however, that this analysis is not capable of expressing task accuracy in terms of sensitivity and bias, and that results of this analysis might be somewhat confounded by different proportions of correct trials (on average 42 %) and incorrect trials (on average 58 %).

Thus, in a second analysis, to obtain a more robust within-subject measure of the brain-behaviour relation, we followed a leave-half-out (LHO) subsampling approach: For each participant, we randomly sampled 50 % of trials in each condition of the 2 (Attended stream: A vs. B) x 2 (Eyes: open vs. closed) design. We repeated this step 1,000 times to obtain 1,000 LHO estimates of d' (termed d'_{LHO}) and criterion (termed c_{LHO}). For the same subsamples we obtained 1,000 LHO estimates of the attentional alpha power modulation (termed attentional alpha modulation_{LHO}). Figure 5A shows d'_{LHO} averaged across participants as a function of the rank-ordered attentional alpha modulation_{LHO}.

For statistical analysis, we obtained the slope (β) for the linear regression of d'_{LHO} on attentional alpha modulation_{LHO} for each participant. In line with the first analysis, slopes were positive on average (across all conditions: $\beta = 0.02$; open eyes: $\beta = 0.025$; closed eyes: $\beta = 0.028$), suggesting a positive relation of alpha power modulation and perceptual sensitivity (d'). However, slopes were not statistically different from zero (across all conditions: $t_{21} = 1.17$; $p = 0.26$; $r = 0.25$; $BF = 0.41$; open eyes: $t_{21} = 1.10$; $p = 0.283$; $r = 0.23$; $BF = 0.38$; closed eyes: $t_{21} = 1.18$; $p = 0.25$; $r = 0.25$; $BF = 0.41$). Taken together, evidence from these two analyses of the brain–behaviour relation speaks to a weak relation at best of the attentional alpha power modulation at the neural level and task performance at the behavioural level.

Of note, the same analysis procedure did not reveal an obvious relationship of attentional alpha modulation_{LHO} and response bias (c_{LHO}; across conditions: $t_{21} = -0.90$; $p = 0.377$; $r = 0.19$; $BF = 0.32$; open eyes: $t_{21} = -0.501$; $p = 0.618$; $r = 0.11$; $BF = 0.25$; closed eyes: $t_{21} = 1.21$; $p = 0.24$; $r = 0.26$; $BF = 0.43$).

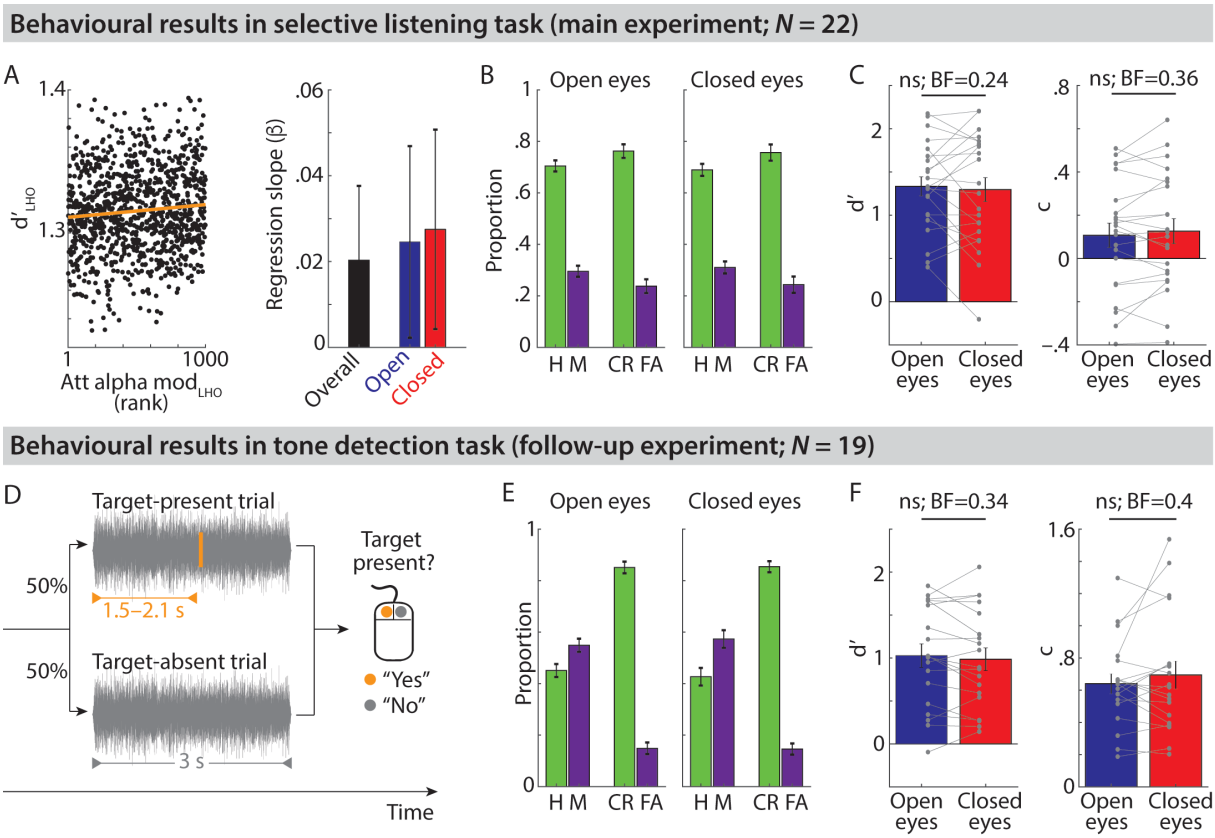

Figure 5. Modulation of behavioural performance in main- and follow-up experiment. (A) Scatterplot shows sensitivity (d'_{LHO}) derived from 1,000 leave-half-out (LHO) subsamples of each participant's data as a function of the attentional alpha modulation$_{LHO}$, averaged across $N = 22$ participants across eyes open and closed conditions in the main experiment. Orange line shows the least-squares linear fit. Bars show average slopes obtained through regression of d'_{LHO} on attentional alpha modulation$_{LHO}$. (B) Bars show average proportions of response types in the main experiment , separately for open and closed eyes (H = Hit, M = Miss, CR = Correct Rejection, FA = False Alarm). (C) Bars and thin lines show respective average and single-subject sensitivity (d') and criterion (c). (D) Task design of the follow-up experiment. Participants ($N = 19$) had to detect a tone (orange; which was present in 50% of trials) in noise (grey). (E & F) Same as A & B, but for the follow-up experiment. Error bars show ±1 between-subject SEM. BF indicates the Bayes Factor for non-significant (ns) effects.

Closing the eyes does not affect behavioural indices of attention and tone detection. Finally, we tested whether closing the eyes would relate to behavioural performance. In the main experiment, perceptual sensitivity in separating to-be-attended from to-be-ignored numbers (d') was well above zero, i.e., chance level (Fig.5C; open eyes: $t_{21} = 12.19$; $p < 0.001$; $r = 0.94$; closed eyes: $t_{21} = 9.36$, $p < 0.001$; $r = 0.9$) but did not differ for closed versus open eyes ($t_{21} = 0.45$; $p = 0.654$; $r = 0.1$; Bayes Factor, $BF = 0.24$). Participants' criterion (c) was larger than zero (open eyes: $t_{21} = 1.9$; $p = 0.071$; $r = 0.38$; closed eyes: $t_{21} = 2.19$; $p = 0.04$; $r = 0.43$), which indicates that participants had an overall conservative bias to respond 'No, ignored' more often. However, the criterion was largely unaffected by eye closure ($t_{21} = 1.03$; $p = 0.313$; $r = 0.22$; $BF = 0.36$).

We further investigated whether the behavioural null-effects of closing the eyes were specific to a task involving selective listening to speech, or whether they would conceptually replicate in a task that does neither involve speech stimuli, nor the necessity to retain target stimuli in memory.

Accordingly, in the follow-up experiment, participants (N = 19) had the task to detect a near-threshold target tone in noise (Fig. 5D). The Signal-to-Noise Ratio (SNR) of the target tone in noise was titrated for each participant before the experiment. The mean titrated SNR was –7 dB (SD = 1.55), which resulted in an average proportion correct of 0.646 (SD = 0.079) in the experiment.

In line with the main experiment, perceptual sensitivity (d') in the follow-up experiment was significantly above zero (Fig. 5E&F; open eyes: $t_{18} = 7.57$; $p < 0.001$; $r = 0.87$; closed eyes: $t_{18} = 7.42$; $p < 0.001$; $r = 0.87$) but did not differ for open compared with closed eyes ($t_{18} = 0.899$; $p = 0.381$; $r = 0.207$; $BF = 0.339$). The response criterion (c) was significantly positive (open eyes: $t_{18} = 10.32$; $p < 0.001$; $r = 0.92$; closed eyes: $t_{18} = 8.03$; $p < 0.001$; $r = 0.88$), indicating a generally conservative bias to respond 'No' (no tone detected) more often. The response criterion did not differ for open versus closed eyes ($t_{18} = 1.083$; $p = 0.293$; $r = 0.247$; $BF = 0.397$).

The small Bayes Factors (BFs) for the non-significant comparisons of sensitivity and criterion for open versus closed eyes in the main experiment as well as in the follow-up experiment lend support to the null hypothesis of no difference in behavioural performance in auditory attention and tone detection with open versus closed eyes.

Discussion

The present study sought to test whether closing the eyes during listening has the potency to enhance neural and behavioural indices of auditory attention. The major findings can be summarized as follows. As expected, closing the eyes during listening increased the level of absolute alpha power. Importantly, however, eye closure amplified the neural alpha power difference in attending versus ignoring speech, that is, the neural separation of relevant and irrelevant acoustic input. Finally, debunking the belief that eye closure per se improves listening, we provide evidence for the absence of an effect of closing the eyes on sensitivity and response criterion for auditory attention and tone detection in two independent experiments.

Closing the eyes shapes absolute alpha power dynamics. In agreement with previous research (e.g., Barry et al., 2007; Geller et al., 2014), eye closure in a darkened room (Adrian and Matthews, 1934; Ben-Simon et al., 2013) almost doubled participants' absolute occipital alpha power in the EEG (Fig. 2). This absolute alpha power increase possibly reflects inhibition of neural processing in visual cortex regions (Jensen and Mazaheri, 2010; Foxe and Snyder, 2011), disengaging these regions when the eyes are closed. Of note, Adrian (1944) was possibly the first to discover that alpha oscillations show a general increase when participants direct their attention to the auditory modality (for more recent studies, see e.g., Foxe et al., 1998; Wöstmann et al., 2015b; Dimitrijevic et al., 2017; Henry et al., 2017). He interpreted this alpha increase as "a positive activity that fills those parts of the cortex which are for the moment unemployed."[2]

We here observe that eye closure propels alpha power outside the dynamic range observed with open eyes (Fig. 2C). Since we used eye closure in this study as a means to modulate alpha power, it can be considered a method of endogenous neuromodulation, comparable to (exogenous) perturbation methods such as transcranial alternating current stimulation (tACS; Herrmann et al., 2013). However, eye closure appears to induce much stronger increases in alpha power, which was also demonstrated by Neuling et al. (2013), who showed that alpha-tACS increases neural alpha power only in a regime of low alpha power with open eyes but not in a regime of high alpha power with closed eyes. In sum, eye

[2] Adrian ED (1944) Brain Rhythms. Nature 153:360-362. P. 361

closure lifted absolute alpha power far above levels observed during attentive listening with open eyes.

Closing the eyes enhances the attention-induced alpha modulation. In the present selective listening task (main experiment), a listener's intent to attend versus ignore spoken numbers was accompanied by respective states of high versus low alpha power (Fig. 3). This agrees with previous findings of alpha power modulation in temporal synchrony with attending versus ignoring speech (Wöstmann et al., 2016b; Tune et al., 2018). Our results speak to the modulation of alpha power over time as a neural signature of auditory attention.

The most important finding of this study was that eye closure not only increased the overall level of absolute alpha power, but also strongly enhanced the attentional modulation thereof. Enhanced alpha power modulation with closed eyes was generally wide-spread in topography but localized mainly in non-auditory, parieto-occipital cortex regions. Alpha power increases in these regions have been associated with inhibitory control of supramodal attention networks (e.g., Banerjee et al., 2011) and visuo–spatial processing areas (e.g., Fu et al., 2001; Wöstmann et al., 2015b). In visual tasks, alpha power modulation in parieto-occipital regions in sync with the stimulus affects stimulus encoding (Bonnefond and Jensen, 2012; Payne et al., 2013; Park et al., 2014). In the present auditory task, however, parieto-occipital alpha power modulation might control the degree of auditory attention through inhibition of task-irrelevant visual processing areas (Strauß et al., 2014). The present results show that closing the eyes is indeed effective insofar as it enhances the degree to which a listener's top-down intention to attend versus ignore speech modulates neural alpha power.

The effect of closing the eyes was specific to the 8–12 Hz alpha frequency range, and observed only for power but not for phase-locking of neural oscillations. This speaks against the possibility that neural responses in general are enhanced with closed compared to open eyes. Furthermore, this indicates that cycles of the eye–closure-modulated alpha oscillation were not evoked (i.e., strictly phase-locked across trials) but rather induced (for distinction of evoked and induced oscillations, see Tallon-Baudry and Bertrand, 1999; Wöstmann et al., 2017).

So, what is the functional significance of larger alpha power modulation with closed eyes? It has been suggested that even in a darkened room with very little visual input, closing the eyes might reduce the cross-modal dominance of the visual system (Brodoehl et al., 2015a) to facilitate attention to non-visual modalities. Eye closure could thus free neural processing capacity, in order to enhance inhibition versus facilitation of respective ignored versus attended auditory stimuli, which eventually surfaces in stronger alpha power modulation. Neural separation of attended and ignored auditory stimuli is a key mechanism of auditory attention (Shinn-Cunningham, 2008) to solve the long-standing Cocktail party problem, that is, listening to one talker against competing distractors (Cherry, 1953). In this respect, alpha power modulation has been considered a filter mechanism to separate attended from ignored auditory input (e.g., Kerlin et al., 2010; Strauß et al., 2014; Wöstmann et al., 2016a). The present results demonstrate that this auditory filter mechanisms surfaces to a stronger extent in the human EEG signal when the eyes are closed.

Effects of eye closure on neural but not behavioural responses. Against the widely held belief that eye closure improves attentive listening, we found no increase in listeners' sensitivity or criterion in telling attended from ignored speech items in the main experiment (Fig. 5). In principle, these null effects might have been caused by nature of our task. Spoken numbers were presented well above participants' hearing thresholds and sensitivity of responses by far exceeded chance level. This contrasts with previous studies in the somatosensory modality where eye closure was found to lower perceptual detection at threshold (Brodoehl et al., 2015b; Brodoehl et al., 2015a). Furthermore, it might be that potential effects of closing the eyes on auditory processing were masked by the fact that task performance in the main experiment depends to large extents also on working memory for the presented numbers. However, the follow-up experiment, which implemented a close-to-threshold tone detection task and was free of potential influences of working memory, conceptually replicated the behavioural null-effects of the main experiment.

We consider three potential reasons for why eye closure was found here to affect neural but not behavioural indices of auditory attention and perception: Issues with sensitivity of our behavioural outcome measure; a mismatch of the imposed neuromodulation (eye closure) and the required neural dynamic range (Jazayeri and Afraz, 2017); and the absence of visual distraction.

First, it might be that our behavioural outcome measures were not sensitive enough to detect any effect of eye closure. We consider this possibility rather unlikely since (i) we found the null-effect both in an auditory selective listening task (main experiment), as well as in a tone detection task (follow-up experiment), (ii) our analyses of sensitivity and response criterion had the power to detect changes in behavioural performance that might be overseen in case only the proportion of correct responses is inspected, and (iii) our Bayesian statistical analysis revealed small Bayes Factors (close to or below .33; Dienes, 2014) for behavioural null-effects, which provide positive evidence for the absence of effects rather than insensitivity of the data. Note, however, that our behavioural null-results do not preclude the possibility that eye closure might be beneficial in other listening scenarios, such as tasks involving auditory spatial attention.

Second, we observed only a weakly positive association between the attentional modulation of alpha power and perceptual sensitivity (Fig. 5A). Thus, increases in the attentional modulation of alpha power do not directly result in sizable improvements of behavioural performance. Furthermore, it might be that those alpha power generators that increased their modulation by closing the eyes did not precisely overlap with alpha generators associated with listening performance. It is known that the impact of neuromodulation on behaviour critically depends on its precision in targeting task-relevant neural processes in time, frequency, and space (e.g., Herrmann et al., 2016; Vosskuhl et al., 2018). Furthermore, neuromodulation might be behaviourally ineffective if it pushes the neurally relevant process outside its natural dynamic range (Jazayeri and Afraz, 2017). In the present study, the eye-closure induced effect on alpha oscillations might have been too massive and spatially wide-spread to impact listening behaviour.

Third, it might be the case that our experimental intervention of closing the eyes was indeed successful in increasing versus decreasing the inhibition of non-auditory regions during respective periods of attending versus ignoring speech. However, our participants performed the main- and follow-up experiment in a darkened chamber, deprived of visual input. Thus, inhibition of non-auditory regions might have been ineffective in modulating behaviour since no non-auditory, distracting stimuli were presented. Although the intention of the present study was to study the sole effect of closing the eyes free from potential influences of the blocking of the visual input, future studies might observe beneficial effects of closing the eyes on listening tasks in more busy visual environments.

Conclusions

Does closing the eyes enhance auditory attention? First, an important neural mechanism of auditory attention, alpha power modulation, has been shown here to be amplified by eye closure. That is, when listeners have their eyes closed, the increased attentional modulation of alpha power indeed implies stronger neural separation of attended and ignored sound sources. Second, however, eye closure per se does not improve auditory attention and tone detection performance. Possibly, the impact of eye closure on neural oscillatory dynamics does not match alpha power modulations associated with listening performance precisely enough. Third, the present findings do have important practical implications for the neuroscience of auditory attention: Researchers should rigorously control whether participants close their eyes during listening. Participants might even be instructed to utilize the endogenous amplification of closing the eyes to increase the power to observe existing attentional effects on neural alpha oscillations.

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