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Impact of communicative head movements on the quality of functional near-infrared spectroscopy signals: negligible effects for affirmative and negative gestures and consistent artifacts related to raising eyebrows

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Abstract. Functional near-infrared spectroscopy (fNIRS) is currently one of the most promising tools in the neuroscientific research to study brain hemodynamics during naturalistic social communication. The application of fNIRS by studies in this field of knowledge has been widely justified by its strong resilience to motion artifacts, including those that might be generated by communicative head and facial movements. Previous studies have focused on the identification and correction of these artifacts, but a quantification of the differential contribution of common communicative movements on the quality of fNIRS signals is still missing. We assessed the impact of four movements (nodding head up and down, reading aloud, nodding head sideways, and raising eyebrows) performed during rest and task conditions on two metrics of signal quality control: an estimative of signal-to-noise performance and the negative correlation between oxygenated and deoxygenated hemoglobin (oxy-Hb and deoxy-Hb). Channel-wise group analysis confirmed the robustness of the fNIRS technique to head nodding movements but showed a large effect of raising eyebrows in both signal quality control metrics, both during task and rest conditions. Reading aloud did not disrupt the expected anticorrelation between oxy-Hb and deoxy-Hb but had a relatively large effect on signal-to-noise performance. These findings may have implications to the interpretation of fNIRS studies examining communicative processes. [DOI: 10.1117/1.JBO.22.4.046010]

Keywords: near-infrared spectroscopy; head movements; quality control.

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1 Introduction

Functional near-infrared spectroscopy (fNIRS) is a brain mapping technique that has been increasingly used in social cognitive neuroscience to examine the regional changes in cerebral hemodynamics and oxygenation underlying the comprehension of other's intentions and the proper reactions to them.[1] One of the main advantages of the fNIRS technique is the possibility of conducting experiments in real-world settings, allowing for the investigation of social interactions in a valid interpersonal context. Alternatively to other modalities, such as functional magnetic resonance imaging and electroencephalography that require relative immobilization of the subject, fNIRS has been proposed to be an effective and reliable technique for studying brain function[2] in experiments involving free movement,[3] human-to-human interaction in language-based communication[4] and cooperation,[5] and in speech perception in infants.[6] The application of fNIRS in ecologically valid social neuroscience with hard-to-test groups of subjects, however, implies that these data will be acquired under higher levels of motion variations that potentially increase the chances of signal quality degradation.

A particular challenge for naturalistic studies examining social communicative neural processes is the fact that signals measured by fNIRS, for example, oxygenated (oxy-Hb) and deoxygenated (deoxy-Hb) hemoglobin, may be contaminated by confounders. For example, head and facial movements used to regulate social interaction (e.g., head nodding and shaking, raising eyebrows) may lead to motion artifacts that can originate from movement-induced mechanical instabilities that stem from the set of factors comprising a particular sensor and head-gear design. Additionally, still expected are variations in the physiological response that accompanies the head/facial movements. For instance, it has been shown that speaking-evoked changes in respiration patterns alter the partial pressure of carbon dioxide in the arterial blood,[7] which in turn alter cerebral blood flow.[8] Moreover, jaw movements associated with speaking, as well as other facial movements, such as frowning, produce contraction of the temporalis muscle, which can also lead to muscular postcontractile blood flow responses.[9] These nonfunctional components are problematic for the correct interpretation of cerebral hemodynamic changes expected to be due to neurovascular coupling.

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It has been suggested that nonfunctional components on fNIRS signals, including those arising from motion artifacts, may manifest as a positive correlation between oxy-Hb and deoxy-Hb, which are typically strongly negatively correlated according to its expected physiology.[10] This positive correlation has been therefore used as a marker for the presence of noise associated with movement artifact.[11,12] In fact, recent recommendations to avoid misinterpretations of fNIRS hemodynamic responses not due to neurovascular coupling as real brain activity emphasize the imperativeness of considering the time dynamics of both oxy-Hb and deoxy-Hb signals and their interrelationship in fNIRS data analysis.[13]

Although several studies have focused on various strategies to compensate for disturbances in data quality that are a consequence of either variations in sensor contact or result from intrinsic responses,[14,15] more basic is to gain an understanding of the differential contribution of common communicative movements on the quality of fNIRS signals. In this study, we therefore assessed the impact of four head and facial movements (nodding head up and down, reading aloud, nodding head sideways, and raising eyebrows) on two metrics of signal quality control: an estimative of signal-to-noise performance and the negative correlation between oxy-Hb and deoxy-Hb. We investigated the effects of each head movement on these metrics during a motor task as well as during resting using a channel-wise analysis. We expect that channels more contaminated with motion artifacts arising from communicative movements will exhibit high signal variation as well as a positive correlation between oxy-Hb and deoxy-Hb concentrations.

2 Material and Methods

2.1 *Participants*

We examined 14 right-handed young male adults (mean age = 25.15 + 3.07 years). All participants were nonsmokers or rare smokers, free of medication except for one subject taking regular antithyroid medication. None of the participants reported a history of neurological diseases. The study was approved by the local ethics committee, and all participants gave written informed consent.

2.2 *Experimental Procedure*

Participants were scanned while performing a right-hand finger tapping task. The block design activation paradigm consisted of 11 epochs of alternating finger tapping/rest conditions. To induce motion-related artifacts during task performance, we adopted a similar procedure described in Yücel et al. At the same time that subjects were performing the finger tapping/rest blocks, they were asked to execute four different types of head and facial movements mimicking typical motions during naturalistic social communication: (1) nodding their head up and down rhythmically with a semantic function of agreement, (2) reading aloud small sentences expressing weather forecast content, (3) nodding sideways expressing negation, (4) brief raisings of their eyebrows expressing general emphasis, and (5) a control condition in which no movement was required from the subject. Each motion trial was performed for 3 s, and trials were repeated four times for each motion type (two trials per block) with a randomized intertrial interval between 5 and 9 s. Figure 1 shows the experimental paradigm, block duration, and the total number of blocks of each condition. Two runs were acquired, each one lasting 10 min. In each run, the measuring cap was secured to the head of the participants using a chin strap or a chest belt to control for variations in optode contact that could arise from specific movements (i.e., speaking). Trials were equally distributed across finger tapping and rest blocks. Runs (chin, chest) and trial order (nodding their head up and down, reading aloud, nodding sideways, and raising their eyebrows) were counterbalanced across subjects. The timing of tapping and rest blocks as well as movement trials were controlled and cued with visual stimuli presented on the screen using the software NIRStim (NIRx Medical Technologies, Glen Head, New York). Before scanning, all subjects were instructed and practiced the task to assure that they understood the task and the communicative intent of the head movements required.

2.3 *Functional Near-Infrared Spectroscopy Acquisition*

The hemodynamic signals for this study were obtained from the optical changes collected using a continuous wave, functional near-infrared spectroscopy system (NIRScout16x16, NIRx Medical Technologies, Glen Head, New York) with 16 LED illumination sources and 16 optical detectors. The sources consist of colocated LEDs emitting two wavelengths (760 and 850 nm) on different modulation frequencies. The optical detectors are based on 240-cm length fiber optic cables that carry the received light back into the imager for signal amplification. The sampling rate was 3.91 Hz.

Sources and detector optodes were placed on the left hemisphere of the measuring cap (128 positions based on the 10-5 international system) provided by the system's manufacturer. The optodes' positions were defined to cover most of the left hemisphere (as shown in Fig. 1) to assess the global effects of physiological noise and movement artifacts on the signals. This layout allowed the measurement of 49 channels of interest as shown in Fig. 2. We defined source–detector pairs with interoptode distance ranging from 20 mm (two channels) to 30 mm (remaining 47 channels). The 30-mm interoptode distance constraint was implemented by using stabilizing links, which were also employed to improve the setup stability and to prevent the tipping of the optodes. In addition to the links, we used cable organizers to facilitate the routing of the fiber optic cables and to relieve mechanical strain.

Fig. 1 Experimental paradigm. Finger tapping and resting blocks (lasting 20 to 31 s) were alternated. Visual cues on the computer screen indicated the beginning and end of each block and of the communicative movements. There were three blocks in which none of the target head/facial movements were required (i.e., control condition).

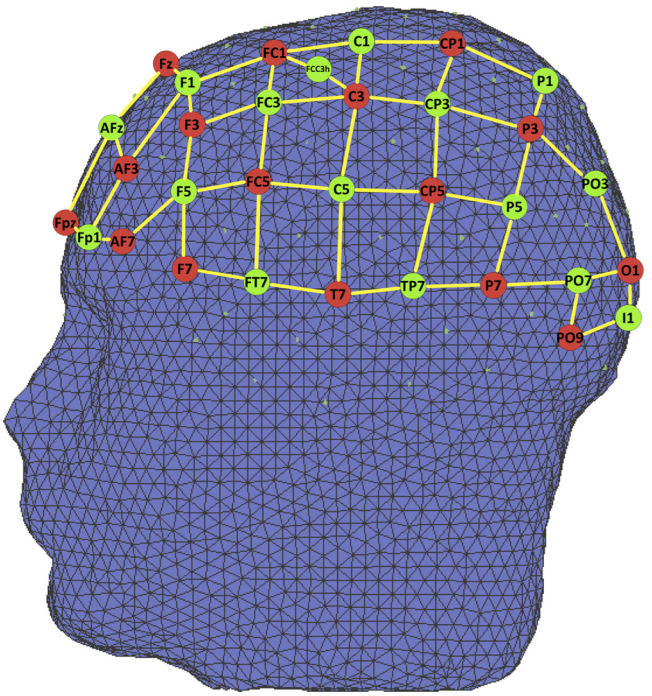

Fig. 2 Illustration of sources (red) and detectors (green) and its correspondent positions in the 10-5 international system.

After placing the cap, we measured the distances between the left and the right preauricular points as well as between the nasion and the inion to assure that the Cz position from the 10-5 international system was centrally placed both in the left–right direction as well as in the anterior–posterior direction. Once the cap was positioned, we secured the cap with a strap. We put it either underneath the chin or around the chest of the subject as one of our goals was to evaluate how robust each strap position would be in the presence of different types of motion artifacts.

Prior to each measurement, an automatic calibration process available in the acquisition software NIRStar (NIRx Medical Technologies, Glen Head, New York) was performed to determine the optimal amplification factor that each source–detector combination should be given to achieve what is considered an optimal range (0.4 to 4.0 V) for the modulated raw signal level. In the following, the quality of the signals was evaluated by considering amplification gain, signal level, and coefficient of variation (CV = standard deviation/mean). If any channel did not pass in quality control, we attempted to improve the signal quality by removing the corresponding source and detector from the cap and making sure that the hair would be kept away of the light path, which was accomplished by applying a clear ultrasound gel (Aquasonic Clear, Parker Laboratories Inc., Fairfield, New Jersey) to hold the hair around the optode position. Finally, once the desired signal quality was achieved, we placed a zipper retaining cap over the measuring cap. The retaining cap was used for shielding the measurement from ambient light and to obtain a better skin-optode contact.

2.4 *Data Preprocessing and Signal Quality Analysis*

The raw intensity data were temporally filtered with a band-pass filter (0.01 to 0.2 Hz) to remove cardiac and respiratory frequencies as well as very low frequency oscillations. After converting the intensity data to optical density, oxy-Hb and deoxy-Hb concentration changes were then calculated using the modified Beer–Lambert equation.[16] All preprocessing steps were carried out using the software nirsLAB_v201412.

The preprocessed data were exported from nirsLAB, and the subsequent steps were carried out in *R* platform for statistical computing. The channel coefficient of variation (CV = standard deviation/mean) of each wavelength was calculated at each timepoint considering a sliding window of 5 s width and the band-pass filtered signal. We used the median CV of each block as a quality control metric of the measured signal during the block, in which the greater the CV, the lower the signal quality. In other words, an increase in the signal's standard deviation in respect to its mean implies a decrease in the signal-to-noise ratio. This is a similar procedure as used and described by Piper et al.[3] to evaluate the influence of motion artifacts during physical exercise.

For this same sliding window of 5 s width, the Pearson correlation coefficient between oxy-Hb and deoxy-Hb concentrations at each channel was calculated to identify, for each motion artifact of interest, which channel positions would yield a positive correlation coefficient.

For each subject, the median CV of the two wavelengths and the correlation between oxy-Hb and deoxy-Hb (across frames) were calculated for each channel and experimental condition.

Finally, paired *t*-tests across subjects comparing the mean oxy-Hb–deoxy-Hb correlations (and CV) of each motion condition in relation to its respective control condition (i.e., resting or finger tapping blocks in which the head communicative movement was not voluntarily performed by participant) were carried out. We intended to analyze the magnitude of the differences from each movement condition to its respective control condition. The signal quality metrics are expected to be different between the blocks with and without the movements, although in some cases, this difference could be negligible. The goal of this study is to quantify the magnitude of the motion artifacts' impact at each channel. It is expected that the null hypothesis of the statistical test (the difference in quality metrics is equal to zero) is false, and consequently, the test would be rejected for a sufficient large N (i.e., p values <0.05). Thus, to avoid this problem as well as the use of arbitrary thresholds for the Type I error, we prefer to present the effect size of the comparisons (instead of p values) by calculating the Cohen's D measure in a channel-wise manner. The Cohen's D was based on the differences of quality metrics across subjects. It was defined as the mean differences divided by the standard deviation of the differences across subjects. Thus, the greater the Cohen's D coefficient, the larger the impact of the artifact on the signal quality. The Cohen's D values for each channel were overlaid into the Montreal Neurological Institute (MNI) template available in the BrainNet Viewer software[17] according to the 10-5 MNI coordinates as reported in Jurcack et al. and freely available in Ref. 18.

3 Results

Figure 3 shows the results of the channel-wise group analysis showing regional effect sizes of changes in the temporal correlation coefficient between oxy-Hb and deoxy-Hb signals for each movement condition in relation to its respective control condition. The vast majority of channels exhibited small effect sizes for both rest and task for almost all motion conditions. The exception was the raising-eyebrows movement condition, which presented the largest impact in the pattern of oxy-Hb–deoxy-Hb

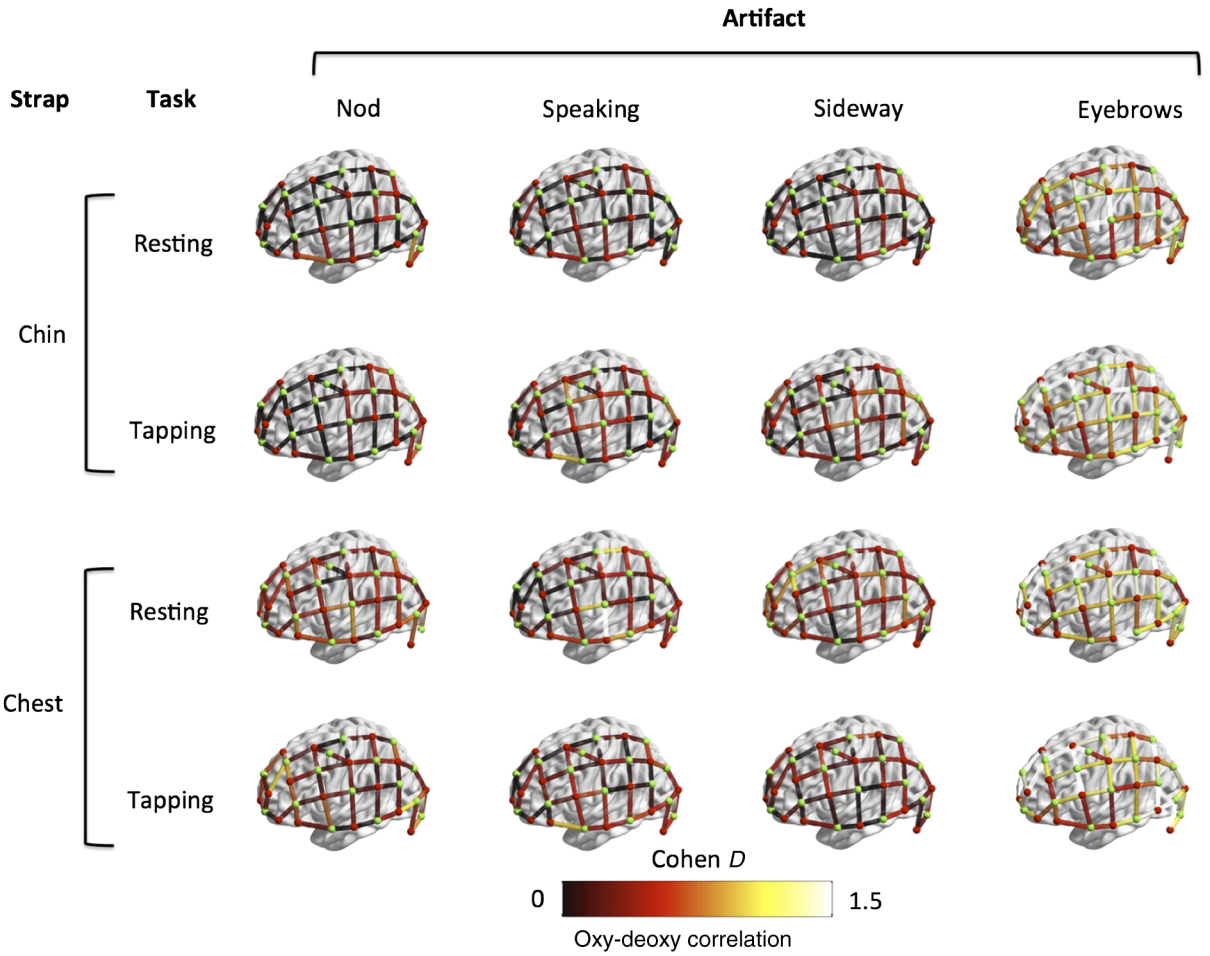

Fig. 3 Effect size (Cohen's *D*) of changes in oxy-Hb–deoxy-Hb correlations for each head movement condition in comparison with its respective control condition. Lower values indicate better signal quality.

correlations in several channels across the scalp. Also, slightly larger effect sizes were observed for the acquisition run with chest strap in comparison with the chin strap run.

Figures 4 and 5 show group average effect sizes for changes in CV of the 760- and 850-nm wavelength, respectively, across the different head motion conditions. Similar to the results obtained with oxy-Hb–deoxy-Hb correlations, most channels across the scalp surface presented a large effect size of raising eyebrows effects on CV changes for both wavelengths. In addition to that, reading aloud (i.e., speaking) presented considerably large effects size for changes in CV of several channels.

To better understand the evoked head movement responses during the finger tapping task blocks, grand average plots were created (Fig. 6) for the filtered intensity data as well as of the hemodynamic responses evoked by each trial of the target movements examined in our study for a channel spanning the primary motor cortex (C3-C5). Visual inspection of the figure first corroborates the robustness of the technique to nod and sideways motion conditions, as previously observed with the CV and correlation metrics. One can also observe a selective high amplitude variations time-locked to eyebrow movements, for both chin and chest strap acquisitions, resulting in a relatively high CV and positive hemodynamic signals correlation. Moreover, it is notable that the speaking time course presents a high CV and a negative oxy-Hb–deoxy-Hb correlation. Further grand average blocks for the time series of the other three channels (Fpz-Fp1, F7-FT7, and O1-I1) are presented in Fig. 7. It can be observed that the pattern of motion-evoked responses across channels is different for some of the movements. The most pronounced differences are observed for the posterior channel (O1-I1) in comparison with the other three channels during the eyebrows movement.

4 Discussion

In the present study, we assessed the impact of motion artifacts triggered by head and facial movements typically performed in naturalistic communicative interaction on the quality of fNIRS signals. Our findings confirm the robustness of the fNIRS technique to head nodding and shaking movements. We also showed that among all examined movement conditions, only raising eyebrows has a large effect on disrupting the expected negative correlation between oxy-Hb and deoxy-Hb while also decreasing signal-to-noise performance in several channels across the scalp. Furthermore, raising-eyebrows effects in these metrics were observed in both task and rest, suggesting that this artifact can disrupt the expected patterns of hemodynamic covariation independent of task condition. Finally, we also observed a considerable effect of reading aloud on the signal-to-noise performance but not on the oxy-Hb–deoxy-Hb correlation.

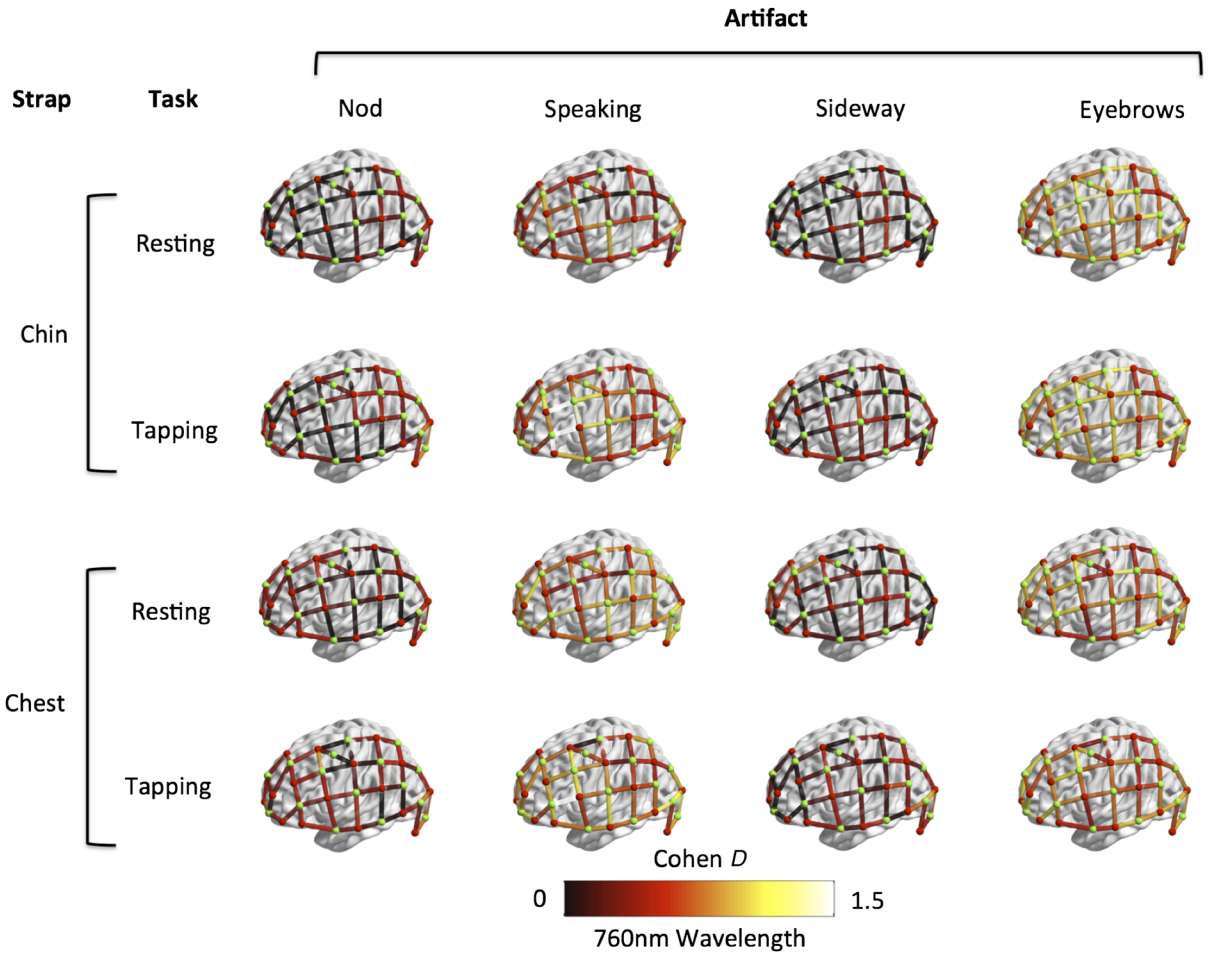

Fig. 4 Effect size (Cohen's *D*) of changes in 760-nm wavelength signal coefficient of variation (CV) for each head movement condition in relation to its respective control condition. Lower values indicate better signal quality.

The negligible effects of up-and-down head nodding as well as sideways nodding on both signal-to-noise ratio and correlation metrics are of great significance for future studies aiming to assess cortical activity in the context of social communication that foresee head movements. This has been demonstrated during task and rest conditions over all measurement channels measuring the left hemisphere of the cortex. We emphasize that these optimal findings depend on the head-gear setup that enables for stable optode-scalp contact during the nodding movements and therefore ensuring no relative movement between the head and the optodes, which would yield spike artifacts. Thus, it is essential to achieve a stable setup that will prevent tipping/pulling of optodes during movements.

The largest effect of raising eyebrows in inducing artifacts in fNIRS signals compared with the other head/facial movements has been noted previously by studies using different acquisition methods and quality control metrics. For example, Yucel et al., comparing the performance of collodion-fixed fiber probe with a standard velcro-based probe in five healthy subjects, reported the highest changes in the raw intensity fNIRS signals as well as in the oxy-Hb and deoxy-Hb concentrations during eyebrow raising. Scholkmann et al.[19] examining differences in the susceptibility of single-distance and multidistance measurement methods to motion, also reported that frowning caused the strongest movement artifacts in the deoxy-Hb signal. Different mechanisms have been proposed to explain this effect. First, muscle contraction associated with raising eyebrows can induce large and spatial distributed motion instabilities in the coupling between optodes and scalp. Second, it has been proposed that muscle contraction follows a neurovascular coupling principle, exhibiting a postcontraction blood flow increase that can be detected as an increase in the magnetic resonance image signal intensity (i.e., blood-oxygenation level dependent effect)[9] as well as an increase in oxy-Hb concentration measured with NIRS.[20] Taken together, these findings highlight the need to specially consider the differential influences that the signals evoked from particular head/facial movements might have on masking hemodynamic data due to neurovascular coupling.

The large effect of reading aloud on signal-to-noise performance in the context of preserved hemodynamic anticorrelation may indicate that these two quality control metrics can reflect different sources of confounders in fNIRS signals. This might be related to a larger variability due to hemodynamic changes triggered by speech in particular channels that had not been engaged during resting or finger tapping conditions. Reduced signal-to-noise ratio (increased CV) during speech may also be related to instabilities of scalp-optode coupling induced by jaw movements as well as to physiological changes in

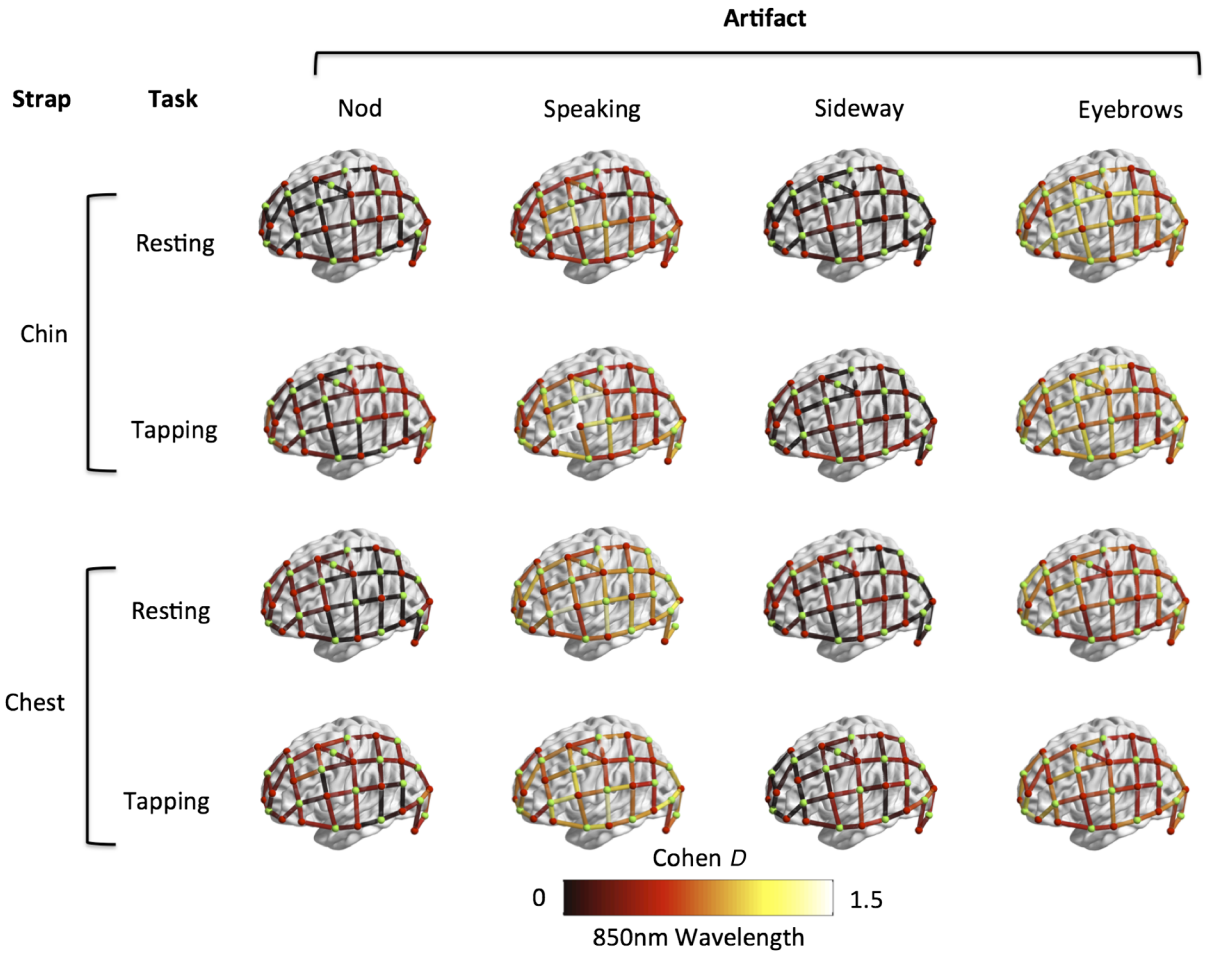

Fig. 5 Effect size (Cohen's *D*) of changes in 850-nm wavelength signal coefficient of variation (CV) for each of head movement condition in relation to its respective control condition. Lower values indicate better signal quality.

respiration evoked by speech tasks.[7] However, as we did not monitor systemic changes (e.g., respiratory), it is not possible to disentangle these factors.

The findings of this study might have some important implications for fNIRS practical users. Interestingly, we found negligible differences in the signal quality regarding the strap fixation at the chin or the chest, which we find to be a relevant finding, as the strap positioning was expected to play a key role depending on the experimental condition of interest (e.g., speaking). Therefore, volunteer comfort can be prioritized when decided where to attach the headgear. Moreover, our findings showing a similar impact of head movements on both rest and task conditions might be particularly important for hyperscanning studies examining dyads of subjects during joint activities. It can be then assumed that in studies examining speaker–listener interactions, for example, the impact of head movements will be observed in subjects performing both active and passive roles. Finally, considering the large impact of raising eyebrows on signal quality control, we would recommend to instruct participants to avoid this kind of movement during the experiment. However, this could not be feasible in naturalistic experiments, and therefore, the use of motion correction algorithms might be imperative.

A number of important limitations of our study need to be considered. First, no anatomical registration of the fNIRS data was carried out. Similar to the vast majority of fNIRS studies in the literature, we used the 10-5 international system of electrode placement. Therefore, correspondence between measured channels and the underlying macroanatomical structure must be cautious. Second, we recognize that fNIRS acquisition systems from other manufacturers might result in different results from those presented herein. For example, these findings strongly depend on the accessories used to avoid relative motion between the scalp and the optodes as well as probes tilting during motion. Although the chosen type of light sources (e.g., LEDs or lasers) and sensors (e.g., silicon or avalanche photodiodes) might yield different absolute CV results, the effect sizes that we observed should not be affected, as these are rather relative measures. In the current study, we chose to use both intensity data (CV) and hemodynamic measures (correlation between oxy-Hb and deoxy-Hb) as quality control metrics for fNIRS. Our choice was motivated to allow for comparisons of CV with those from previous studies and also because a negative correlation between oxy-Hb and deoxy-Hb measurements is expected. Moreover, we acknowledge that for a more quantitatively accurate estimation of the amount of noise produced by the head movements investigated here, future studies are required using accelerometers or at least video recordings. Finally, for a better understanding of the origins of the movement-induced signal degradation, we suggest simultaneously

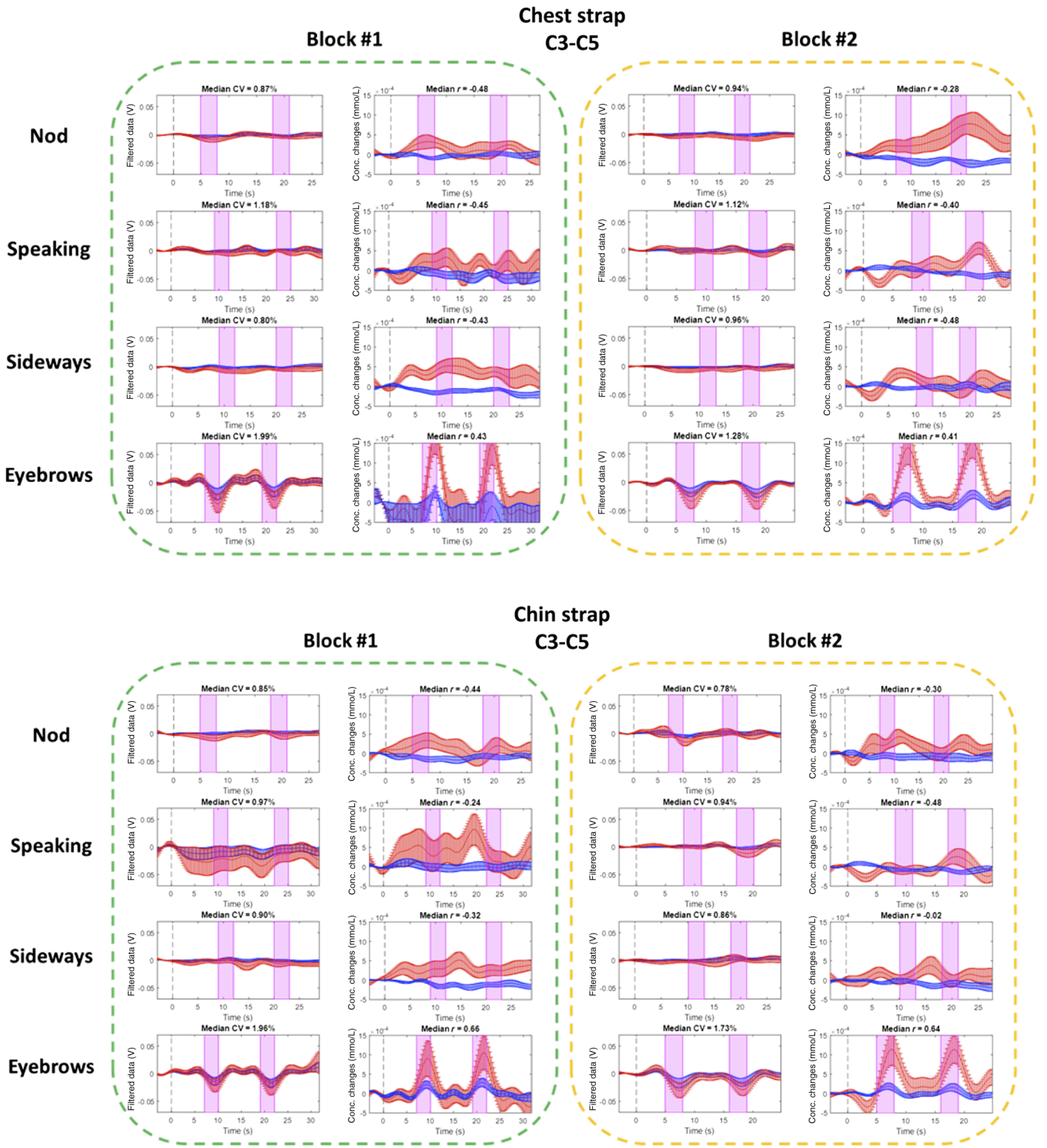

Fig. 6 Results of the group average of fNIRS data. Block averages of filtered intensity and hemodynamic signals of oxy-Hb (red) and deoxy-Hb (blue) from channel C3-C5 spanning the primary motor region over all subjects during finger tapping are depicted. The error bars indicate the standard error of the mean across subjects. The periods of the motion trials are indicated in pink.

monitoring systemic variables using, for example, short-distance channels and/or breath and heart rate monitoring.

In conclusion, we believe our findings reinforce the robustness of fNIRS against artifacts induced by head movements with communicative content. Except for raising eyebrows, we overall found negative correlation coefficients between oxy-Hb and deoxy-Hb. We also found acceptable levels of signal-to-noise ratio overall across conditions, apart from raising eyebrows and speaking, which strongly affected the signal quality assessed with the CV for both wavelengths. Our results should be taken into account for the design, acquisition, analysis, and interpretation of fNIRS studies with the goal to assess

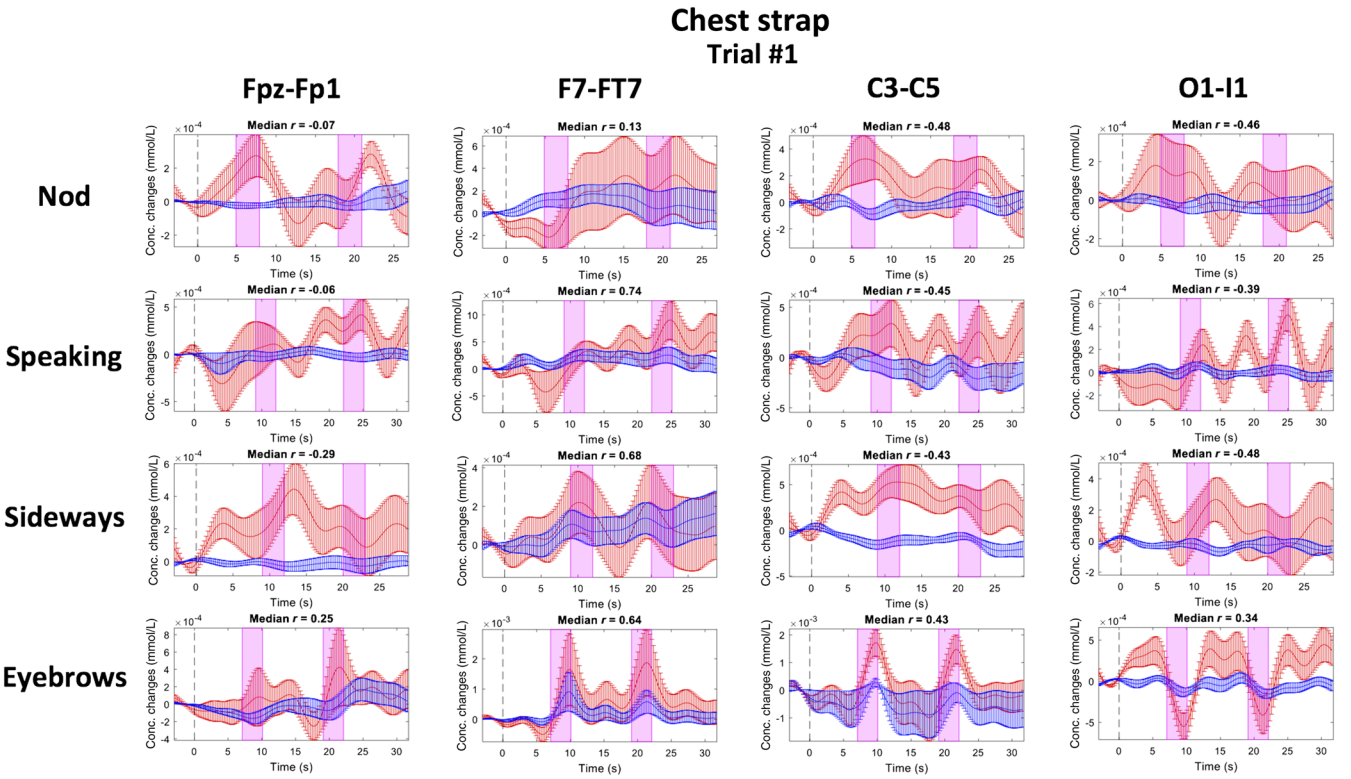

Fig. 7 Results of the group average of fNIRS data. Block averages of filtered intensity and hemodynamic signals of oxy-Hb (red) and deoxy-Hb (blue) from channels Fpz-FP1, F7-FT7, C3-C5, and O1-I1 over all subjects during finger tapping are depicted. The error bars indicate the standard error of the mean across subjects. The periods of the motion trials are indicated in pink.

social communication. Finally, we believe that further research and development of noise and artifact reduction packages combining different measures, for example, short-distance separations, accelerometer as well as breath and heart rate monitoring, can prove important to enable the proper application of fNIRS data collection and interpretation in naturalistic measurements.

Disclosures

GAZM is employed by NIRx Medizintechnik GmbH. All other authors declare no conflicts of interest.

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Biographies for the authors are not available.