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Advancing NIRS-Based Insights into Motor Imagery and Execution of Swallowing: Effects of Artifact Correction Methods and Hemodynamic Validation

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ABSTRACT: Motor imagery (MI) of swallowing has proven to be a promising mental strategy for brain-computer interface (BCI) and neurofeedback applications aimed at treating swallowing difficulties. Previous near-infrared spectroscopy (NIRS) studies demonstrated comparable hemodynamic responses over the inferior frontal gyrus during motor execution (ME) and MI of swallowing, particularly for deoxygenated hemoglobin. However, due to the reliance on manual artifact rejection, it remained unclear whether these findings were influenced by motion artifacts. In this study, 33 healthy young adults were tested, and their hemodynamic responses during ME and MI of swallowing were assessed using NIRS. By applying advanced and automated motion artifact correction methods, such as wavelet filtering and short-distance channel regression, the results were largely consistent with previous studies that used manual artifact rejection. This validates earlier findings and confirms that the observed activation patterns in the hemodynamic response were not primarily caused by motion artifacts, demonstrating the robustness of prior conclusions. When directly comparing motion artifact correction methods (manual rejection, wavelet filtering, and short-distance channel regression), wavelet filtering effectively reduced concentration changes in oxygenated hemoglobin compared to manual correction, indicating fewer motion artifacts. In contrast, short-distance channel regression showed no significant effects, underscoring the need for further optimization of correction methods and the importance of selecting appropriate artifact correction techniques in NIRS studies investigating ME and MI of swallowing.

INTRODUCTION

Previous studies using near-infrared spectroscopy (NIRS) to investigate the hemodynamic response during motor execution (ME) and motor imagery (MI) of swallowing have shown that ME leads to an increase in HbO (oxygenated hemoglobin) and HbR (deoxygenated hemoglobin) in frontal brain regions, whereas MI results in a decrease in HbO and an increase in HbR, likely reflecting inhibition of active swallowing [1–4]. The strongest activations were observed in the inferior frontal gyrus (IFG) for both ME as well as MI [1, 2, 5]. Furthermore, neurofeedback studies demonstrated that it is possible to upregulate HbR in the IFG during MI of swallowing, suggesting that MI-based neurofeedback could be a promising tool for the treatment of dysphagia [3, 5, 6].

Although NIRS is a robust method for measuring brain activity, it is susceptible to unsystematic variations caused by physiological noise and motion artifacts. The signal, which originates from light passing through the scalp and skull to the cortex, contains not only the hemodynamic response from neuronal activation but also noise from cardiac signals, arterial blood pressure oscillations (Meyer waves), respiration, and other physiological changes in extracortical layers. While high-frequency noise can be filtered out, low-frequency changes like Meyer waves are harder to detect and may correlate with the signal [7–10]. Additionally, motion artifacts, caused by optode displacement or scalp movements from jaw or eyebrow activity, can distort the signal in various forms, such as spikes, baseline shifts, or low-frequency variations. These artifacts may occur as isolated events or overlap with task-related hemodynamic responses, making them difficult to distinguish [9, 11].

Especially swallowing movements leading to jaw movements produce significant motion artifacts in NIRS signals due to strong temporal muscle activity [12]. Previous studies addressing neuronal correlates of swallowing relied on visual inspection and manual rejection of motion artifacts [1, 2, 13]. This approach is highly subjective and poses challenges in distinguishing motion artifacts from the hemodynamic response [8, 10, 11]. To ensure the comparability between ME and MI of swallowing and to establish MI as a potential tool for dysphagia therapy using it as a mental strategy in brain-computer interface (BCI) and neurofeedback applications, it is crucial to confirm that MI of swallowing elicits brain activation patterns comparable to those of ME.

Recent advancements in NIRS technology, such as the

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use of short-distance (SD) channels and correction techniques like wavelet filtering, provide improved insights into the true hemodynamic response in signals affected by motion and physiological artifacts [8, 14, 15]. SD channels are a method used in NIRS studies to isolate and remove physiological noise originating from extracortical layers, such as the scalp and skull. Unlike standard long-distance channels, where the source and detector optodes are spaced approximately 3 cm apart to capture signals from both cortical and extracortical layers, SD channels place the detector close to the light source. This setup ensures that the detected signal originates only from extracortical layers [16, 17]. By simultaneously measuring signals at multiple distances, SD channels allow researchers to regress extracortical noise from cortical activation, improving signal quality [16, 18]. This approach complements other external instruments, such as pulse sensors, respiratory belts, or EMG, for extracting interfering measures from NIRS signals [7, 15, 19].

Wavelet filtering has been successfully applied as artifact correction method in speech studies, where motion artifacts were stimulus-dependent [8]. Wavelet filtering is a channel-by-channel approach that assumes signal components follow a normal distribution, with outliers attributed to motion artifacts [20]. Outliers, defined by the interquartile range, are set to zero, and the signal is recomposed using an inverse discrete wavelet transformation. This method preserves most of the frequency content and is effective for correcting spikes [8, 14].

The aim of this study was to validate previous findings [1–3] using a modern NIRS system equipped with SD channels and wavelet filtering, and to evaluate the effectiveness of these correction methods compared to manual artifact rejection. Therefore, we compared different NIRS artifact removal methods (SD, wavelet, manual rejection) and investigated their effects on the hemodynamic response elicited by ME and MI of swallowing. This study has two main objectives: (1) to validate and replicate previous findings on the hemodynamic response during ME and MI of swallowing using more advanced artifact handling methods (wavelet filtering and SD channel regression) and (2) to investigate the effectiveness of wavelet filtering and SD channel regression for motion artifact correction in NIRS signals.

MATERIALS AND METHODS

Participants: 33 healthy young adults between 18-35 years (20 females, 13 males) participated in the present study. All participants gave their written informed consent and the study was approved by the local ethics committee of the University of Graz (GZ. 39/4/63 ex 2020/21).

Task: In the present study, a motor execution (ME) and motor imagery (MI) task similar to [1, 2] were used, involving saliva swallowing instead of water. Participants performed 20 ME and 20 MI trials, each lasting 15 seconds, presented in randomized order. During ME trials, participants swallowed their saliva 5–6 times at a comfortable pace, while during MI trials, they imagined swallowing at the same pace using a kinesthetic approach. Task instructions were displayed on a computer screen using PsychoPy [21], with the letter "A" indicating ME and "V" indicating MI, and triggers marking task onsets and offsets in the signal. Between tasks, a fixation cross was shown for 28–32 seconds, during which participants were instructed to avoid active swallowing. All participants received brief training before the task.

NIRS-recordings: The hemodynamic response during the ME/MI tasks was recorded using a NIRSport 2 system (NIRx Medizintechnik, GmbH, Berlin, Germany), a continuous wave system with LED sources emitting light at 760 and 850 nm wavelengths. The system measured changes in oxy- (HbO), deoxy- (HbR), and total hemoglobin in the cortex. The probe setup included eight source and seven detector optodes mounted on an EEG cap, ensuring a 30 mm distance between each source-detector pair (long-distance channels). Additionally, eight short-distance detectors were placed 8 mm from the source optodes (SD channels), requiring one long-distance detector to be repurposed. The sampling rate was set to 10.2 Hz, and NIRx software (NIRSite 2.0 and Aurora fNIRS 1.4) was used for channel configuration and data recording. The probe setup was positioned bilaterally above the IFG and included regions such as the dorsolateral prefrontal cortex, premotor and supplementary motor cortex, frontal eye fields, middle and superior temporal gyrus, subcentral area, primary somatosensory cortex, supramarginal and angular gyrus (Wernicke), and somatosensory association cortex, following previous NIRS studies on ME/MI of swallowing [1, 2]. Visualizations of the probe setup (see Fig. 1) and recorded data were generated using AtlasViewer [22], a MATLAB-based software package. Channel pairs S2-D4, S4-D3, and S4-D4 over the left hemisphere and channel pairs S6-D7, S8-D6, and S8-D7 over the right hemisphere covered the IFG (Fig. 1).

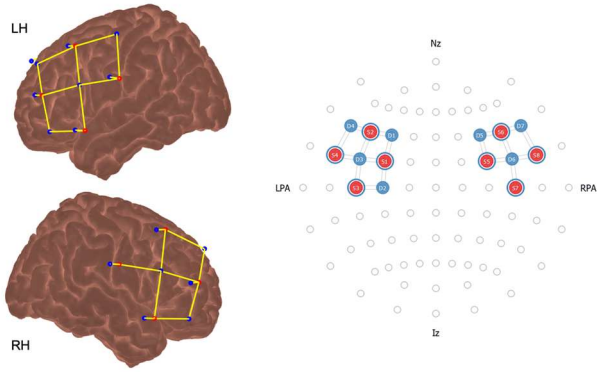

Figure 1: The NIRS probe was positioned over the left (LH) and right (RH) hemispheres. Red markers represent source optodes, blue markers indicate both long- and short-distance detectors, yellow lines illustrate corresponding source-detector pairs.

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NIRS data preprocessing: NIRS data preprocessing was performed using the MATLAB-based program Homer2 (Huppert et al., 2009), comparing four artifact correction methods. Raw optical density (OD) data was converted into OD changes using the Homer2 function *hmrIntensity2OD*, and channels with low OD were discarded via *enPruneChannels*. Motion artifacts were corrected either with wavelet filtering (*Wav and Wav + SD*) using *hmrMotionCorrectWavelet* (iqr = 0.1) or manually (*manual* and *manual + SD*).
Motion artifacts were further detected and excluded using *hmrMotionArtifact* and *enStimRejection*. All pathways applied high-pass (0.01 Hz) and low-pass (0.50 Hz) filters via *hmrBandpassFilt* to remove physiological noise, followed by conversion to HbO and HbR concentration changes using *hmrOD2Conc*. For SD-channel regression, *hmrDeconvHRF_DriftSS* was used to remove hemodynamic drift. HbO and HbR changes were baseline-referenced to 5 seconds before stimulus onset (-5 to 0 seconds).
Block averages were calculated for -5 to 40 seconds around stimulus onset using *hmrBlockAvg*. After visual inspection, two participants were excluded due to poor data quality, leaving 31 participants. Data was averaged for Task (5–15 seconds) and Pause (15–25 seconds) intervals for ME and MI separately, using Homer's *Export Mean Results* function.

Statistical analysis: To assess the topographical distribution of significantly activated brain areas, paired sample *t*-tests were conducted comparing the activation interval (5–25 seconds) to the baseline (-5–0 seconds) for each channel, condition (ME and MI), and hemoglobin type (HbO and HbR). Significant changes were identified using the false discovery rate (FDR) method to correct for multiple comparisons [23]. For this analysis, only data processed with wavelet filtering and SD channel regression was included to compare the current findings with previous NIRS studies that relied solely on manual artifact rejection (e.g., [1]) in order to determine whether different artifact handling techniques yield varying results.
Regions of interest (ROIs) were defined based on [1, 2] for comparability, targeting channels associated with the left (channel pairs: S2-D4, S4-D3, S4-D4) and right IFG (channel pairs: S6-D7, S8-D6, S8-D7; see Fig. 1).
To analyze HbO and HbR changes during ME and MI, two separate 2x2x2 repeated-measures ANOVAs were performed with within-subject factors *Task* (ME vs. MI), *Time* (Task vs. Pause), and *Hemisphere* (Left vs. Right), using HbO and HbR concentration changes as dependent variables. Again, to confirm whether earlier findings that relied solely on manual artifact correction (e.g., [1]) were influenced by motion artifacts, this analysis included only data processed using wavelet filtering and SD channel regression to validate those results.
Additionally, two 2x2 repeated-measures ANOVAs were conducted to compare motion artifact correction methods, with factors *Correction Method* (Wavelet vs. Manual) and *SD-Channel Regression* (Yes vs. No). HbO and HbR concentration changes during the ME task (5–15 seconds) were used as dependent variables, as motion artifacts are most prominent during active swallowing. To account for differences in hemodynamic response function (HRF) scaling across correction methods, HbO and HbR values were standardized via z-transformation within subjects across all methods.

RESULTS

The FDR analysis revealed that the strongest NIRS signal changes were observed over the bilateral IFG, mainly in the channel pairs merged for the left and right IFG ROIs (e.g., for ME HbO, the five strongest significant channel pairs were S8-D7, S4-D4, S2-D3, S4-D3, and S8-D6; number of sign. channel pairs ME HbO: 18; MI HbO: 18; ME HbR: 3; MI HbR: 2). HbO increased during ME but not during MI, while HbR increased during ME as well as MI (see Fig. 2).

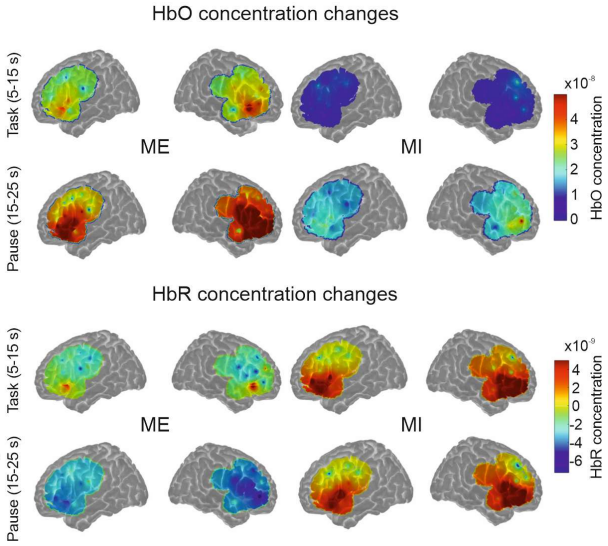

Figure 2: Topographical distributions of HbO and HbR changes averaged for the Task and the Pause interval, presented separately for the motor execution (ME) and motor imagery (MI) conditions.

For HbO, the 2x2x2 repeated-measures ANOVA for NIRS data preprocessed with wavelet filtering and SD channel regression revealed a significant main effect for *Task* ($F(1,29) = 27.61$, $p < .001$, $\eta_p^2 = .488$), indicating higher activation during ME ($M = .063$ m(mol/l) * mm, $SE = .005$) compared to MI ($M = .015$ m(mol/l) * mm, $SE = .008$). Additionally, a significant main effect for *Time* was found ($F(1,29) = 38.77$, $p < .001$, $\eta_p^2 = .572$), with higher HbO levels during the Pause interval ($M = .055$ m(mol/l) * mm, $SE = .007$) compared to the Task interval ($M = .023$ m(mol/l) * mm, $SE = .004$). A significant interaction between *Hemisphere* and *Time* ($F(1,29) = 15.46$, $p < .001$, $\eta_p^2 = .348$) showed greater activation in the right hemisphere ($M = .061$ m(mol/l) * mm, $SE = .008$) compared to the left hemisphere ($M = .023$ m(mol/l) * mm, $SE = .005$) during the Pause interval (see Fig. 2). The interaction between *Task* and *Time* almost reached significance ($F(1,29) = 4.00$, $p = .055$, η_p^2

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= .121), suggesting higher HbO during Pause (M = .082 m(mol/l) * mm, SE = .008) compared to Task (M = .045 m(mol/l) * mm, SE = .004) for ME, while MI showed a slight increase during Pause (M = .029 m(mol/l) * mm, SE = .010) compared to Task (M = .002 m(mol/l) * mm, SE = .007). All other effects were not statistically significant: *Hemisphere* ($F(1,29) = 2.02$, $p = .166$, $\eta_p^2 = .065$), *Task*Hemisphere* ($F(1,29) = 1.76$, $p = .195$, $\eta_p^2 = .057$), and *Task*Time*Hemisphere* ($F(1,29) = .00$, $p = .959$, $\eta_p^2 = .000$).

The analysis of HbR concentration changes revealed a significant main effect of *Task* ($F(1,29) = 9.72$, $p < .01$, $\eta_p^2 = .251$), with higher activation during MI (M = .011 m(mol/l) * mm, SE = .005) compared to ME (M = -.004 m(mol/l) * mm, SE = .002). Additionally, a significant interaction between *Task* and *Time* was found ($F(1,29) = 5.67$, $p < .05$, $\eta_p^2 = .163$), showing a reduction in HbR concentration during the Pause interval for ME (M = -.007 m(mol/l) * mm, SE = .003) compared to the Task interval (M = .001 m(mol/l) * mm, SE = .002). Fig. 2 illustrates this interaction effect. No other effects reached statistical significance: *Time* ($F(1,29) = 1.81$, $p = .189$, $\eta_p^2 = .059$), *Hemisphere* ($F(1,29) = 0.27$, $p = .610$, $\eta_p^2 = .009$), *Time*Hemisphere* ($F(1,29) = .00$, $p = .948$, $\eta_p^2 = .000$), *Task*Hemisphere* ($F(1,29) = 1.50$, $p = .230$, $\eta_p^2 = .049$), and *Task*Time*Hemisphere* ($F(1,29) = 0.01$, $p = .910$, $\eta_p^2 = .000$).

The 2x2 repeated-measures ANOVA for HbO comparing the different artifact correction methods revealed a significant main effect of *Correction Method* ($F(1,29) = 35.36$, $p < .001$, $\eta_p^2 = .549$), with manual correction (M = .612 z-transf. m(mol/l) * mm, SE = .103) resulting in higher HbO levels compared to wavelet filtering (M = -.612 z-transf. m(mol/l) * mm, SE = .103). The main effect of *SD-Channel Regression* was marginally significant ($F(1,29) = 3.11$, $p = .088$, $\eta_p^2 = .097$), suggesting slightly higher HbO levels without SD regression (M = .062 z-transf. m(mol/l) * mm, SE = .035) compared to with SD regression (M = -.062 z-transf. m(mol/l) * mm, SE = .035). The interaction between *Correction Method* and *SD-Channel Regression* was not statistically significant ($F(1,29) = 2.18$, $p = .150$, $\eta_p^2 = .070$).

For HbR, no significant effects were observed for *Correction Method* ($F(1,29) = 2.07$, $p = .161$, $\eta_p^2 = .067$), *SD-Channel Regression* ($F(1,29) = 0.626$, $p = .435$, $\eta_p^2 = .021$), or the interaction between *Correction Method* and *SD-Channel Regression* ($F(1,29) = 0.23$, $p = .638$, $\eta_p^2 = .008$).

DISCUSSION

This study aimed to replicate and extend previous NIRS findings on cortical activation during ME and MI of swallowing, which has the potential to be a useful mental strategy in BCI and neurofeedback applications to treat dysphagia symptoms [2, 3, 5, 6]. Earlier studies showed that ME increases both HbO and HbR levels, while MI leads to increased HbR and decreased HbO, with the strongest changes observed in the IFG [1–3]. Given the possibility of motion artifacts caused by simultaneous muscle activation during swallowing [12], this study applied advanced artifact correction methods, including wavelet filtering and SD-channel regression, to validate and refine previous results. These techniques are effective in reducing noise unrelated to cortical activation [8, 14] and were compared to manual artifact rejection used in earlier studies.

When employing advanced motion artifact reduction techniques, such as wavelet filtering and regressing SD channel information from the NIRS signal, the topographical distribution of HbO and HbR remains consistent with previous NIRS studies that relied solely on manual artifact rejection. The strongest signal changes were observed over the IFG [1, 2]. These results successfully replicate earlier findings, demonstrating that prior findings were not merely influenced by jaw movement artifacts during ME of swallowing [1, 2].

This study successfully replicated and extended previous findings on cortical activation during ME and MI of swallowing, confirming that ME leads to higher HbO levels, while MI results in increased HbR and decreased HbO. These findings are consistent with earlier research [1, 2] and align with studies on MI of other movements, which also report weaker HbO activation during MI compared to ME [24]. The reduced HbO activation during MI may be attributed to the absence of actual movement and sensory feedback, as well as inhibitory mechanisms that prevent unintentional swallowing during MI [1, 25]. Interestingly, HbO levels during MI decreased during the task but increased steadily during the resting period, a pattern commonly observed in MI of swallowing but not in MI of other movements [26, 27]. This may reflect the complexity and reflexive nature of swallowing, which involves effortful inhibitory processes [1].

The study also found that HbO levels were significantly higher during the Pause interval following both ME and MI, indicating a prolonged hemodynamic response compared to other movements [26]. This prolonged time course is consistent with earlier studies on swallowing [1, 2] and may be explained by the duration and complexity of the swallowing process itself [28].

Regarding lateralization, HbO levels during the resting period were higher in the right hemisphere, while no hemispheric differences were observed during the tasks. Previous studies have reported predominantly bilateral activation during swallowing [1], but neuroimaging studies suggest lateralization effects depending on the type of bolus swallowed. For example, water swallowing tends to activate the right hemisphere more strongly, while saliva swallowing shows left-dominant activation [4, 29]. The right lateralization observed in this study during voluntary saliva swallowing may reflect insula activation, as suggested by [30], and could have been masked by motion artifacts in earlier studies. However, the lateralization effect during resting periods was small and may also be influenced by interindividual differences in gustatory sensations, as the anterior insula processes taste stimuli [29].

In contrast to HbO, MI resulted in stronger HbR

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concentration changes compared to ME, with HbR levels decreasing over time during ME (comparing Task and Pause intervals). Similar findings were reported in previous research on ME and MI of swallowing, although these effects were primarily observed during a pause interval, while during the task itself, HbR levels were higher for ME than MI [1]. However, as [1] did not apply advanced motion artifact correction methods, such as wavelet filtering or SD-channel regression, the elevated HbR concentrations during active swallowing in their study may have been influenced by motion artifacts caused by muscle activity during swallowing [12, 31].

To sum up, motion artifacts caused by muscle activity during swallowing [12, 31] were addressed in this study using advanced correction methods, including wavelet filtering and SD-channel regression. These methods effectively reduced noise unrelated to cortical activation, providing a clearer NIRS signal. The results were largely consistent with previous studies that relied on manual artifact rejection [1–4], validating earlier findings and confirming that the observed activation patterns in the HRF were not primarily due to motion artifacts. This demonstrates the robustness of prior conclusions and highlights the value of advanced artifact correction techniques in NIRS research.

Furthermore, this study compared different motion artifact correction methods for NIRS signals during ME of swallowing, focusing on wavelet filtering, SD-channel regression, and manual artifact rejection. Wavelet filtering significantly reduced HbO signal changes compared to manual rejection, indicating fewer motion artifacts. This method has been effective in speech studies with task-related artifacts (Brigadoi et al., 2014), but in the present study, the chosen iqr parameter (0.1) may have been overly conservative, potentially reducing the hemodynamic response itself [32]. Adjusting the iqr could help preserve the characteristics of the HRF during swallowing.

For HbR, no significant effects were observed for wavelet filtering or SD-channel regression, consistent with previous findings that HbR is more robust against physiological noise [7]. SD-channel regression, applied after wavelet filtering, showed no additional benefits, likely due to the already corrected data. While SD-channels are effective in reducing physiological noise from the scalp [11, 15], their role in addressing motion artifacts caused by muscle activity remains unclear.

The study also highlighted limitations in the sensitivity of the analysis to detect effects of correction methods. Measures like signal-to-noise ratios (SNR) or trial retention rates could provide better insights into the effectiveness of artifact correction techniques, especially in clinical populations where trial numbers are limited [2]. Visual inspection revealed no rejected trials for wavelet filtering, while manual rejection excluded numerous trials, which may be problematic in studies with fewer trials.

Overall, wavelet filtering proved effective in improving HbO signal quality during swallowing, while SD-channel regression showed potential for enhancing signal quality without compromising data. Future studies should consider applying SD-channels alongside wavelet filtering to further refine NIRS signals in swallowing research [11, 14].

CONCLUSION

In summary, the present study successfully replicated earlier findings on ME and MI of swallowing [1–3], while applying automatic motion artifact correction methods. Hemodynamic signal changes during ME and MI were largely comparable in their topographical distribution and exhibited a prolonged time course. However, differences in HbR concentration changes between ME and MI suggest that motion artifacts may have influenced results in previous studies to some extent [1, 2].

Regarding motion artifact correction, wavelet filtering reduced HbO concentration changes, indicating a decrease in motion artifacts, while no significant effects of SD-channel regression were observed. Future research should explore different measures and parameter settings, such as the iqr, to optimize correction methods.

In conclusion, the study replicated most earlier findings on ME and MI of swallowing [1, 2]. However, the observed differences between manual artifact rejection and wavelet filtering highlight the critical importance of selecting appropriate motion artifact correction methods in NIRS studies investigating swallowing.

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