Chapter 12
The Effect of Inner Speech on Arterial CO_2 and Cerebral Hemodynamics and Oxygenation: A Functional NIRS Study

Felix Scholkmann, Martin Wolf, and Ursula Wolf

Abstract The aim of the present study was (i) to investigate the effect of inner speech on cerebral hemodynamics and oxygenation, and (ii) to analyze if these changes could be the result of alternations of the arterial carbon dioxide pressure ($PaCO_2$). To this end, in seven adult volunteers, we measured changes of cerebral absolute [O_2Hb], [HHb], [tHb] concentrations and tissue oxygen saturation (StO_2) (over the left and right anterior prefrontal cortex (PFC)), as well as changes in end-tidal CO_2 ($P_{ET}CO_2$), a reliable and accurate estimate of $PaCO_2$. Each subject performed three different tasks (inner recitation of hexameter (IRH) or prose (IRP) verses) and a control task (mental arithmetic (MA)) on different days according to a randomized crossover design. Statistical analysis was applied to the differences between pre-baseline, two tasks, and four post-baseline periods. The two brain hemispheres and three tasks were tested separately. During the tasks, we found (i) $P_{ET}CO_2$ decreased significantly ($p<0.05$) during the IRH (~3 mmHg) and MA (~0.5 mmHg) task. (ii) [O_2Hb] and StO_2 decreased significantly during IRH (~1.5 μM; ~2 %), IRP (~1 μM; ~1.5 %), and MA (~1 μM; ~1.5 %) tasks. During the post-baseline period, [O_2Hb] and [tHb] of the left PFC decreased significantly after the IRP and MA task (~1 μM and ~2 μM, respectively). In conclusion, the

F. Scholkmann
Biomedical Optics Research Laboratory, Division of Neonatology, University Hospital Zurich, Zurich 8091, Switzerland

Institute of Complementary Medicine, University of Bern, Imhoof-Pavillon, Inselspital, 3010 Bern, Switzerland

M. Wolf
Biomedical Optics Research Laboratory, Division of Neonatology, University Hospital Zurich, Zurich 8091, Switzerland

U. Wolf (✉)
Institute of Complementary Medicine, University of Bern, Imhoof-Pavillon, Inselspital, 3010 Bern, Switzerland
e-mail: ursula.wolf@kikom.unibe.ch

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study showed that inner speech affects $PaCO_2$, probably due to changes in respiration. Although a decrease in $PaCO_2$ is causing cerebral vasoconstriction and could potentially explain the decreases of $[O_2Hb]$ and StO_2 during inner speech, the changes in $PaCO_2$ were significantly different between the three tasks (no change in $PaCO_2$ for MA) but led to very similar changes in $[O_2Hb]$ and StO_2. Thus, the cerebral changes cannot solely be explained by $PaCO_2$.

12.1 Introduction

In previous studies, we showed that guided rhythmic speech exercises in the context of arts speech therapy (AST) cause changes in heart rate variability [1, 2], cardiorespiratory interactions [3], as well as hemodynamics and oxygenation in the brain and muscle [4–6]. In particular, we demonstrated that during speech exercises, a decrease in cerebral hemodynamics and oxygenation occurred. We hypothesized that this effect might be the result of a decrease in the partial pressure of carbon dioxide in the arterial blood ($PaCO_2$) during speaking [5, 6]. This hypothesis was confirmed in a subsequent study [4]: we found significant changes in end-tidal CO_2 ($P_{ET}CO_2$), a reliable and accurate estimate of $PaCO_2$ [7], during all recitation tasks and even during the control task (mental arithmetic). We concluded that changes in breathing (hyperventilation) during the tasks are mainly to account for the measured changes in hemodynamics and oxygenation mediated by hypocapnia. To further investigate the effect of $PaCO_2$ variations on hemodynamics and oxygenation and in order to avoid a CO_2 reaction, the aim of the present study was to investigate the impact of inner speech tasks on these parameters.

12.2 Material and Methods

Seven healthy subjects (four men, three women, mean age 34.6 ± 9.3 years) participated in this study. The study was carried out as a controlled and randomized cross-over trial. The design of the study was in accordance with the Declaration of Helsinki; the approval was obtained from the Ethical Committee of the Canton of Zurich. The participants were German/Swiss German native speakers who had no previous knowledge of AST and were asked not to eat and consume any stimulants (such as caffeine or other ingredients in energy drinks) for at least 2 h before the start of the measurements. Each subject was measured while performing three different tasks, i.e., inner recitation (i.e., reciting without voicing aloud) of hexameter (IRH) or prose (IRP) verses and a control task (mental arithmetic (MA)). Each task was performed on a separate day to avoid potential carry-over effects, and each measurement lasted 38 min (8 min pre-baseline, 5 min task, 5 min recovery, 5 min task, and 15 min recovery). During the measurements, the subjects sat opposite a

speech therapist who recited the respective text verse by verse or asked the subjects to perform the MA task. The subject repeated the texts with inner speech.

The following physiological parameters were measured: (i) heart rate (device: Medilog AR12 Plus, Schiller AG, Baar, Switzerland; sampling rate, 4,096 Hz, 16 bit); (ii) absolute concentrations of oxyhemoglobin ([O_2Hb]), deoxyhemoglobin [HHb], total hemoglobin ([tHb]), and tissue oxygen saturation (StO_2) (device: OxiplexTS, ISS Inc., Champaign, USA; sampling rate, 50 Hz); and (iii) $P_{ET}CO_2$ (device: Nellcor N1000 gas analyzer, Nellcor. Inc, Hayward, USA; sampling rate, 50 Hz; measurement range, 0–60 mmHg). The NIRS sensors were placed on the left and right side of the forehead over the left and right anterior prefrontal cortex (PFC) and the $P_{ET}CO_2$ probe directly below the right nostril of the subject. The placement of the sensors is illustrated in Fig. 12.1c.

Movement artifacts in [O_2Hb], [HHb], [tHb], and StO_2 signals were removed using the method presented in [8]. Thereby, care was taken to ensure that no artificial new trends were introduced to the signals. Measurements with too many artifacts were excluded from further analysis. The $P_{ET}CO_2$ signal was calculated by using the raw CO_2 waveform signal, detecting the local maxima of every respiratory cycle and determining the envelope over these local maxima. Each time series was segmented into intervals with a length of 3 min each (see Fig. 12.2). For further analysis, all signals were downsampled to 5 Hz and the NIRS-derived signals were low-pass filtered using a moving average filter (window length, 10 s).

The measured changes of [O_2Hb], [HHb], [tHb], StO_2, and $P_{ET}CO_2$ were then tested on their statistical significance by calculating the median values for each segment, normalizing every median value by subtracting the median value from the first interval (to remove the intra-individual variance of the starting values) and applying the Wilcoxon signed-rank test to test for the null hypothesis that the median values for each interval have a distribution with a zero median. Whether the changes in the left and right PFC are statistically different or not was tested with a Wilcoxon rank sum test. This test was also used to test for group differences. All calculations were performed using Matlab (MathWorks, Natick, Massachusetts, USA).

12.3 Results

Figure 12.1a, b shows the measured changes in [O_2Hb], [HHb], [tHb], StO_2, and $P_{ET}CO_2$ for the right and left PFC and the three different tasks. *During the tasks* (i.e., *intervals 2 and/or 4*), StO_2 and [O_2Hb] decreased significantly ($p < 0.05$) in the right PFC during IRH (~1.5 μM; ~1.5 %), IRP (~1 μM; ~1.5 %), and MA (~1 μM; ~1.5 %) tasks. The left PFC showed a less consistent pattern of decreases: while StO_2 and [O_2Hb] decreased in all three tasks, the decreases were only significant for StO_2 during IRP (~2 %) and for [O_2Hb] during IRP (~1.5 μM) as well as IRH (~1.5 μM). A significant increase of [HHb] took place in the right PFC during MA (~0.5 μM) and IRP (~0.2 μM). [tHb] decreased significantly in the right PFC

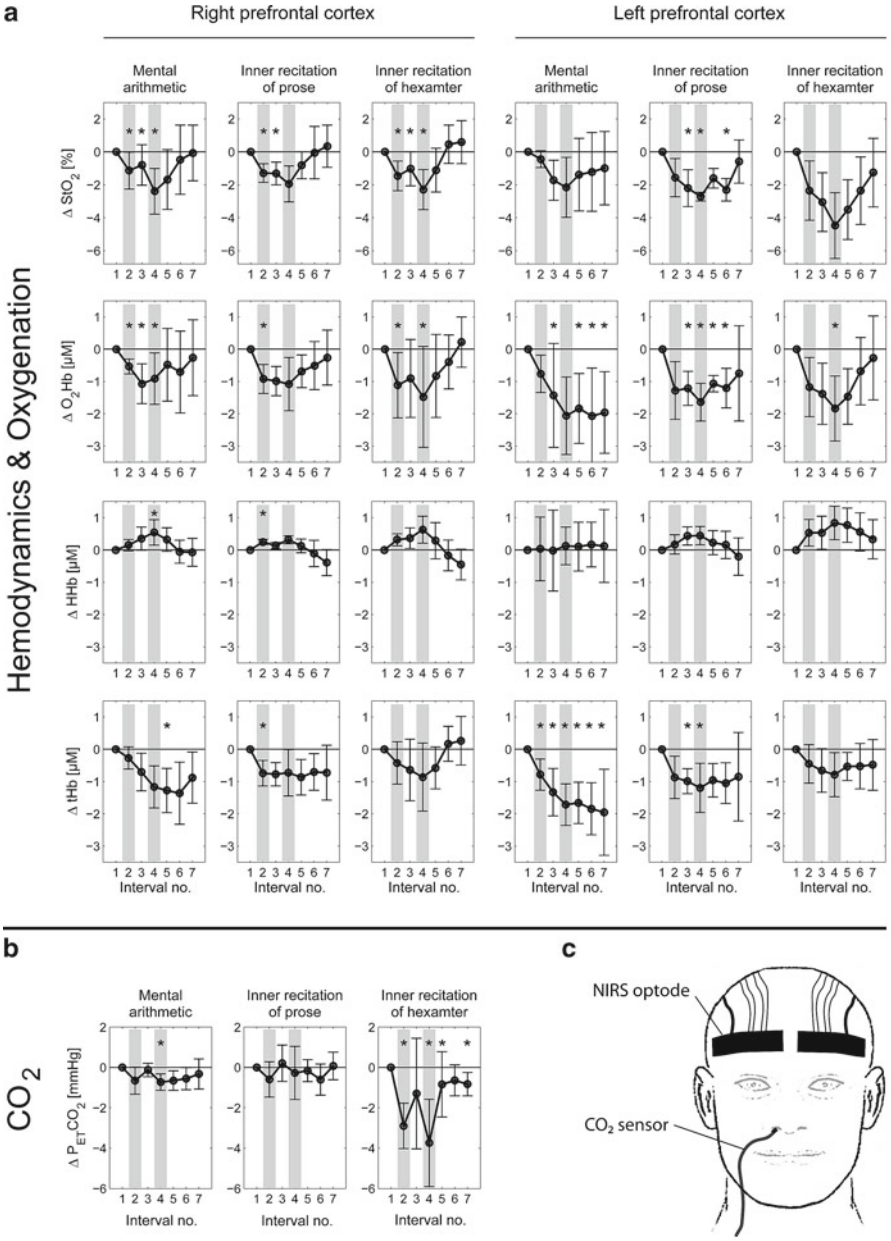

Fig. 12.1 Changes in StO_2, $[O_2Hb]$, [HHb], [tHb] (subfigures **a**), and $P_{ET}CO_2$ (subfigures **b**) over the course of the experiments. Each interval refers to a time span of 3 min. The *shaded areas* indicate the periods when the tasks were performed. All data were shown as median values (*black circles*) ± median absolute deviation (*MAD*). Significant changes are marked with an *asterisk*: $p < 0.05$ (*). Subfigure **c** illustrates the placement of the NIRS probes and the CO_2 sensor on the head of the subject

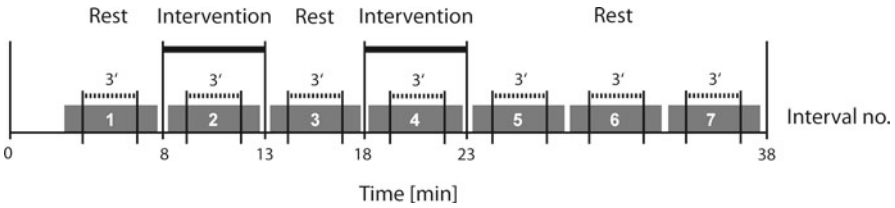

Fig. 12.2 Experimental paradigm

during IRP (~0.5 μM) and in the left PFC during MA (~1.5 μM) as well as IRP (~1 μM). *During the post-baseline period* (i.e., *intervals no 5–7*), $[O_2Hb]$ and [tHb] of the left PFC decreased significantly after the IRP and MA task (both ~2 μM). $P_{ET}CO_2$ decreased significantly during IRH (~3 mmHg) and MA (~0.5 mmHg). The differences in $[O_2Hb]$, [HHb], [tHb], and StO_2 changes between the right and left PFC were not statistically significant. The comparison of the $[O_2Hb]$, [HHb], [tHb], StO_2, and $PETCO_2$ changes with respect to the three different tasks showed that the changes in $PETCO_2$ during the IRH task differed significantly from changes during IPR and MA.

12.4 Discussion

As already indicated in [4], in order to explain the results obtained from speech studies, one should be aware that the measured changes of NIRS-derived hemodynamic and oxygenation signals are the result of at least two major physiological effects. One the one hand, increased neuronal activity leads to an increase in the cerebral metabolic rate of O_2 ($CMRO_2$) which is accompanied by an increase of the cerebral blood flow (CBF) and thus volume (CBV) (neurovascular coupling) [9]. This effect in characteristic changes of the NIRS-derived signals: $[O_2Hb]$ ↑, [HHb] ↓, [tHb] ↑, and StO_2 ↑. On the other hand, changes in $PaCO_2$ have a strong effect on cerebral hemodynamics and oxygenation, i.e., an increase of the frequency and/or volume of breathing (hyperventilation) causes a decrease in $PaCO_2$ (hypercapnia) which leads to a reduction in CBF by cerebral vasoconstriction [10]. This effect is also associated with characteristic changes of the NIRS-derived signals: $[O_2Hb]$ ↓, [HHb] ↑, [tHb] ↓, and StO_2 ↓. The measured changes of the NIRS-derived signals are a combination of both these effects.

The observed significant decrease of $P_{ET}CO_2$ as well as StO_2, $[O_2Hb]$, and [tHb] during all three tasks indicates that the neurovascular coupling seems to be overruled by a hyperventilation-induced hypocapnia which causes a cerebral vasoconstriction. However, it is not clear why the changes in $P_{ET}CO_2$ were significantly different between the three tasks (no change in $P_{ET}CO_2$ for MA) but led to very similar changes in $[O_2Hb]$ and StO_2. This is unexpected since $PaCO_2$ and CBF are almost linearly correlated in the normal physiological range [11]. Thus, the hemodynamic

and oxygenation changes cannot solely be explained by $PaCO_2$. Differences in brain activity related to the specific type of task might also explain the results obtained. It is known that at least two factors are influencing mainly the activity of the PFC: stress [12, 13] and specific types of cognitive activity (particularly memory retrieval and multitasking) [14]. Since the three different types of task in our experiment could be associated with different amounts of evoked stress as well as memory retrieval and multitasking, the ratio of neurovascular coupling/CO_2-mediated effects might differ which would explain the variability of the obtained data.

For further research, it would be interesting to investigate (i) what role silent articulation during the inner speech tasks plays on cerebral hemodynamic and oxygenation changes and (ii) how the effects depend on population-characterizing parameters (i.e., age, gender, type of personality). Additionally, (iii) one should consider to place the NIRS optode over the left inferior frontal gyrus since it was shown that this region is associated with inner speech [15].

In conclusion, the study showed that inner speech effects cerebral hemodynamics and oxygenation primarily by changes in $PaCO_2$ caused by variations in respiration and secondarily by increased neuronal activity of the PFC.

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