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The teaching and the learning brain: A cortical hemodynamic marker of teacher–student interactions in the Socratic dialog



Lisa Holper^{a,1,*}, Andrea P. Goldin^{b,1}, Diego E. Shalóm^{b,1}, Antonio M. Battro^c, Martin Wolf^a, Mariano Sigman^b

^a Biomedical Optics Research Laboratory (BORL), Division of Neonatology, University Hospital Zurich, Frauenklinikstrasse 10, 8091 Zurich, Switzerland

^b Laboratory of Integrative Neuroscience, Physics Department, Faculty of Exact and Natural Sciences, University of Buenos Aires, Argentina

^c National Academy of Education, Buenos Aires, Argentina

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ABSTRACT

The study aimed to step into two-person (teacher–student) educational neuroscience. We describe a physiological marker of cortical hemodynamic correlates involved in teacher–student interactions during performance of a classical teaching model, the Socratic dialog. We recorded prefrontal brain activity during dialog execution simultaneously in seventeen teacher–student pairs using functional near-infrared spectroscopy (fNIRS). Our main finding is that students, who successfully transferred the knowledge, showed less activity than those who not showed transfer. Correlation analysis between teacher and student activity indicate that in successful educational dialogs student and teachers ‘dance at the same pace’. This is the first study measuring simultaneously brain activity of teacher–student interactions and paves future investigations of brain networks involved in complex educational interactions.

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1. Introduction

There is a remarkable gap between our understanding of the mechanisms by which we learn (Gilbert, Sigman, & Crist, 2001) and those by which we teach (Battro, 2010), with the notable exception of some works that suggested that teaching is a natural cognitive ability which develops spontaneously in children (Strauss, 2005; Ziv & Frye, 2004). The enormous growth in understanding human cognitive brain development has created an entirely new way to consider how learning, teaching and the achievement of knowledge take place in education. Educational environments therefore present unprecedented opportunities for cognitive science (Goswami, 2006).

Teaching is a social interaction involving a pupil and a teacher. This is in fact an intrinsically related process as noted by Seneca's famous quote: *docendo discimus*, ‘when we teach we learn’. With the development of portable and wearable equipment it is now possible to investigate the teacher–student dialog in its natural niche. In line with Schilbach et al. (in press) who recently suggested that social cognition is fundamentally different when we interact with others rather than merely observing them, investigating teacher–student interactions may therefore contribute to a better understanding of

* Corresponding author. Tel.: +41 44 255 97 92; fax: +41 44 255 44 42.

E-mail addresses: holper@ini.phys.ethz.ch (L. Holper), apgoldin@gmail.com (A.P. Goldin), diegoshalom@gmail.com (D.E. Shalóm), abattro@ross.org (A.M. Battro), Martin.Wolf@usz.ch (M. Wolf), sigman@df.uba.ar (M. Sigman).

¹ These authors contributed equally to this work.

the neural correlates underlying educational practices and, in the long term, to draw conclusions on how to implement improvements in current classroom practices and teachers education.

Previous neuroimaging studies have conducted experiments in interacting subjects. As recently reviewed by [Babiloni and Astolfi \(in press\)](#), several studies applying hyperscanning methodologies using both hemodynamic or neuro-electric modalities have shown how different brain recording devices have been employed in different experimental paradigms to gain information about the subtle nature of human interactions. However, so far, no studies investigated the interaction between two brains in an educational setup.

The current work is a first step in this direction. A natural caveat to the investigation of the teacher–student dialog is its intrinsic variability. An educational dialog can in fact follow an indefinite number of different paths. Our solution to this potential difficulty is to rely in a classical model of teacher–student interaction, the so-called Socratic dialog. Two thousand four hundred years ago Plato wrote *Meno* his celebrated dialog where Socrates discusses about whether virtue could be acquired by way of teaching or whether it is given to man by nature ([Crane, 2000](#)). Socrates gave a remarkable lesson of geometry, perhaps the first detailed record of a pedagogical method in vivo in history. In brief, Socrates asked *Meno's* slave 50 questions requiring simple additions or multiplications. The boy answered mostly by yes or no. At the end of the lesson the slave discovered the solution by himself, i.e. how to duplicate a square using the diagonal of the given square as the side of the new one.

In a previous study ([Goldin, Pezzatti, Battro, & Sigman, 2011](#)), we demonstrated the universality of this classical model, confirming that a contemporary version of the Socratic dialog shows remarkably similar trajectories, reflecting the same pattern of errors and correct responses. This showed that the dialog was built on an intuition of human reasoning which persists more than twenty-four centuries after its conception. In particular, the consistency of the dialog allows repeating the same paths across subjects, and hence makes it an ideal experimental vehicle to explore the physiological correlates of learning and teaching brains.

2. Materials and methods

2.1. Subjects

17 pairs of subjects were included in the analysis; all subjects (70% females; mean age 24, range 18–74) were Spanish native speakers and right-handed (mean laterality quotient = 76.5; range 47–100; mean decile = 5.8, range 1–10), except one left-handed subject (laterality quotient = –87, decile = 7), according to the Edinburgh Handedness Inventory ([Oldfield, 1971](#)). Five additional pairs were excluded from analysis due to missing data recording in one of the subjects. None of the subjects had any history of neurological or psychiatric disorder or any current medication; all subjects had normal or corrected-to-normal vision. All subjects gave informed consent. All experiments had ethics approval and were reviewed by an external Ethics Committee. The study was in accordance with the latest version of the Helsinki declaration.

2.2. Experimental protocol

Each session consisted of four periods performed by a pair of subjects, one representing the role of the teacher and the other the role of the student, sitting in front of each other in a quiet room.

The dialog consisted of an almost literal version of the Socratic dialog (*'Meno'*) as described in detail by [Goldin et al. \(2011\)](#). The participants playing the role of the teacher were previously instructed to follow a structured dialog. In brief, the dialog consists of 50 questions representing a structured discourse about an arithmetical problem with the main question: how to double the area of a square? The dialog aims to support the student in discovering the solution by self-elaboration, by guiding the student through three kinds of questions: mandatory questions are asked regardless of the student's answers; conditional questions are only asked if the student makes an error; linear questions are followed sequentially unless students made the correct discovery which made subsequent questions illogical. The duration of the whole dialog was therefore dependent on the student's responses passed throughout the dialog. After completing the 50 questions students were again shown the initial question on a new square of a different size and were asked to draw the correct solution. All drawings were documented on paper. All answers were video- and tape-recorded using a web cam (QuickCam[®] for Notebooks Pro, Logitech[®]).

Before and after the dialog two quiet periods with a minimum of 2 min each were included, in which both the student and the teacher were instructed to sit still and minimize body and eye movements. The first of these periods was used to set a baseline for analyses; the second of these periods was defined as *'Rest'* condition. At the end of *Rest* another control condition was included consisting of an approximately 10 min dialog (*'Meletos'*). This dialog took place between Socrates and Meletos and appeared in *The Apology of Socrates* ([Plato, 2008](#)). It resembles the sort of responses, answers and timing of the experimental dialog. Both the student and the teacher were given *Meletos* dialog on paper and were instructed to simply read aloud, each one taking over a part of this dialog.

2.3. NIRS instrumentation

Both the student and the teacher were recorded simultaneously using wireless fNIRS sensors ([Muehlmann, Haensse, & Wolf, 2008](#)) ([Fig. 1](#)). The sensor components are mounted onto a four-layer rigid-flexible printed circuit board (PCB) which, in

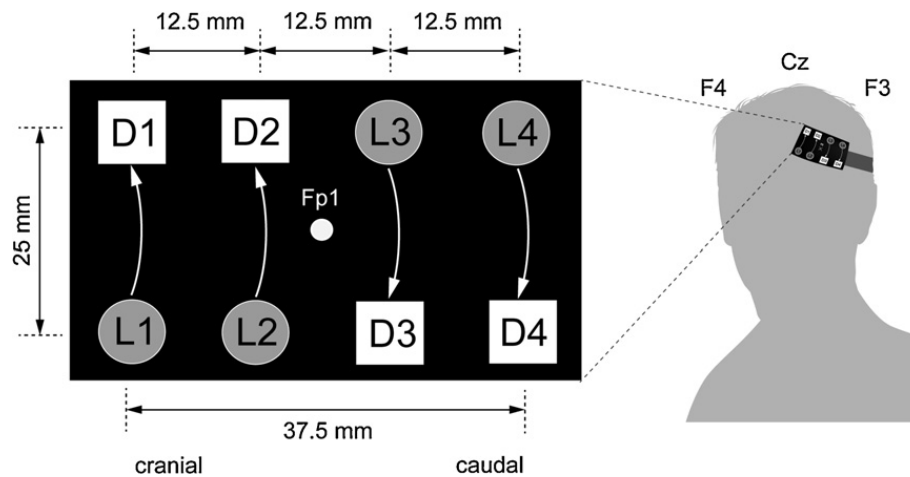


Fig. 1. Wireless fNIRS sensor. Schematic top-view of four channels (Ch 1, Ch 2, Ch 3 and Ch 4) consisting of four light sources (L1, L2, L3, and L4) and four detectors (D1, D2, D3, and D4). The sensor center covered position Fp1 according to the 10–20 system (Jaspers, 1958). D1-L1 was positioned in cranial direction, D4-L4 in caudal direction.

combination with a highly flexible casing made of medical grade silicone, enables the sensors to be aligned to curved body surfaces such as the head. The size of the devices is 92 mm × 40 mm × 22 mm and it weighs 40 g. The optical system comprises four channels with four light sources at two different wavelengths (760 nm and 870 nm) and four light detectors (PIN silicon photodiodes). The power is provided by a rechargeable battery, which allows continuous data acquisition for 180 min at full light emission power. The light intensity is sampled at 100 Hz and the resulting data are transmitted wirelessly to a host computer by Bluetooth® within an operating range of about 5 m.

For fNIRS recording, two sensors were placed over the teacher's and student's left hemispheres, covering Fp1 according to the international 10–20 system (Jaspers, 1958). With each compact sensor measuring an area of 37.5 mm length and 25 mm width, we assumed to cover left prefrontal cortical areas. Hair under the sensors were carefully brushed away to ensure good skin contact and sensors were fixed on the participants' head with homogeneous contact pressure over the whole sensor surface.

2.4. Data analysis

2.4.1. Video processing and event definition

Digital video processing was done offline. Videos were transcribed and the time courses of the following predefined marks were manually set using the software Expression Encoder (Microsoft® Expression Encoder 4®, Version 4.0.1651.0). Seven types of marks specified different dialog events that we did not consider separately for the analyses due to the highly different type and duration of the marks in all dialogs. Hence, these marks were collapsed to one mark defining the Meno dialog ('Meno'). Two other marks were defined when the teacher or student were reading aloud the Meletos dialog ('Meletos'). Both quiet periods were defined as marks 'Baseline' (pre-dialog) and 'Rest' (post-dialog). A MATLAB® (Version 2008a) script was written to subsequently synchronize the event marks with the fNIRS time series.

2.4.2. fNIRS data processing

A program was written in MATLAB® to pre-process the raw light intensity values. By applying the modified Beer-Lambert law (MBLL), from the measured absorption changes of NIR light after its transmission through tissue the concentration over time for oxy- [O₂Hb] and deoxy-hemoglobin [HHb] were computed, which represent the dominant light absorber for living tissue in the NIR spectral band (Abbot, Cope, Delpy, Wyatt, & Reynolds, 1988; Delpy, Cope, Zee, Arridge, Wray, & Wyatt, 1988). First, the NIRS signals were sampled at 100 Hz for all four source-detector combinations, wavelengths and detectors. The ambient light intensities from the fNIRS measurement values were subtracted before taking the logarithm and low-pass filtering (7th order Chebyshev with 20 dB attenuation at 5 Hz) and the signals were then decimated to a sampling rate of 10 Hz. Then, the MBLL was used to compute the changes of [O₂Hb] and [HHb] applying differential path length factors (DPF) of 6.75 for the 760 nm and 6.50 for the 870 nm light sources (Zhao et al., 2002). The linear signal drift was then subtracted from the resulting [O₂Hb] and [HHb] signals. Source-detector combinations (channels) that showed severe artifacts or had a very low signal-to-noise ratio were excluded from analysis. For the same reason channel 4 was excluded from analysis. In all analyses performed, channels 1–3 presented very similar values, presumably due to the low spatial resolution of the fNIRS device. For this reason, we averaged those channels 1–3 for all the analyses and present the data as a coarse measure of prefrontal activity.

2.4.3. Effects of dialog's periods and averaged hemodynamic changes

The time series of raw [O₂Hb] and [HHb] from each participant were corrected subtracting the mean hemoglobin value over the baseline period. Statistical significance of the averaged hemodynamic changes was assessed using ANOVAs with the

fixed factors 'concentration' ($[O_2Hb]$ vs $[HHb]$) 'condition' (Meno, Rest, Meletos) and 'transfer' (yes or no) for students or teachers separately. Post hoc comparisons with t-test and alpha level ($p \leq 0.05$) were applied. Correlation coefficients between teacher and student were calculated using $[O_2Hb]$ for each condition. Significance p -values were log-transformed for clearer presentation.

3. Results

3.1. Behavioral data

The duration from the beginning to the end of the total Meno dialog was 11.6 min averaged over all dialogs. Averaged durations (mean \pm SD) for the teachers' questions and for the students' responses were 7.85 ± 7.39 s and 5.03 ± 4.72 s, respectively. Averaged durations for the other conditions are: rest periods (2.73 ± 0.57 min), Meletos dialog (5.29 ± 2.21 min). On average, students answered 32.18 ± 8.94 out of 50 questions ($63.09\% \pm 17.53\%$) (Fig. 2 (middle)). The responded questions were categorized as *Meno-correct* (implies that the answer given by the subject is the same answer given by the slave, even though it might (and generally is) mathematically wrong) and *Meno-incorrect* (implies that the answer given by the subject is different than the slave's one (and generally this is because our subject responded mathematically correct)). The percent of agreement between our students and the Socratic dialog was measured using the formula $p(\text{Agreement}) = P(\text{Identical}_{\text{response}|\text{responded}})$. In accordance with our previous findings (Goldin et al., 2011), we found a tight agreement between responses of the Socratic dialog and the participants of this experiment. In 31 out of 50 questions all participants, without exception, responded exactly as Meno's slave. On average, the degree of agreement was 90% (Fig. 2 (top and middle)). Probability of responding (regardless of agreement) for each question is shown as $p(\text{passage})$ in Fig. 2 (bottom).

Only a few minutes after completion of Meno dialog, we asked students to double the area of a square of a different size (question 51). This simple procedure was used in our previous study and demonstrated a surprisingly low degree of transfer

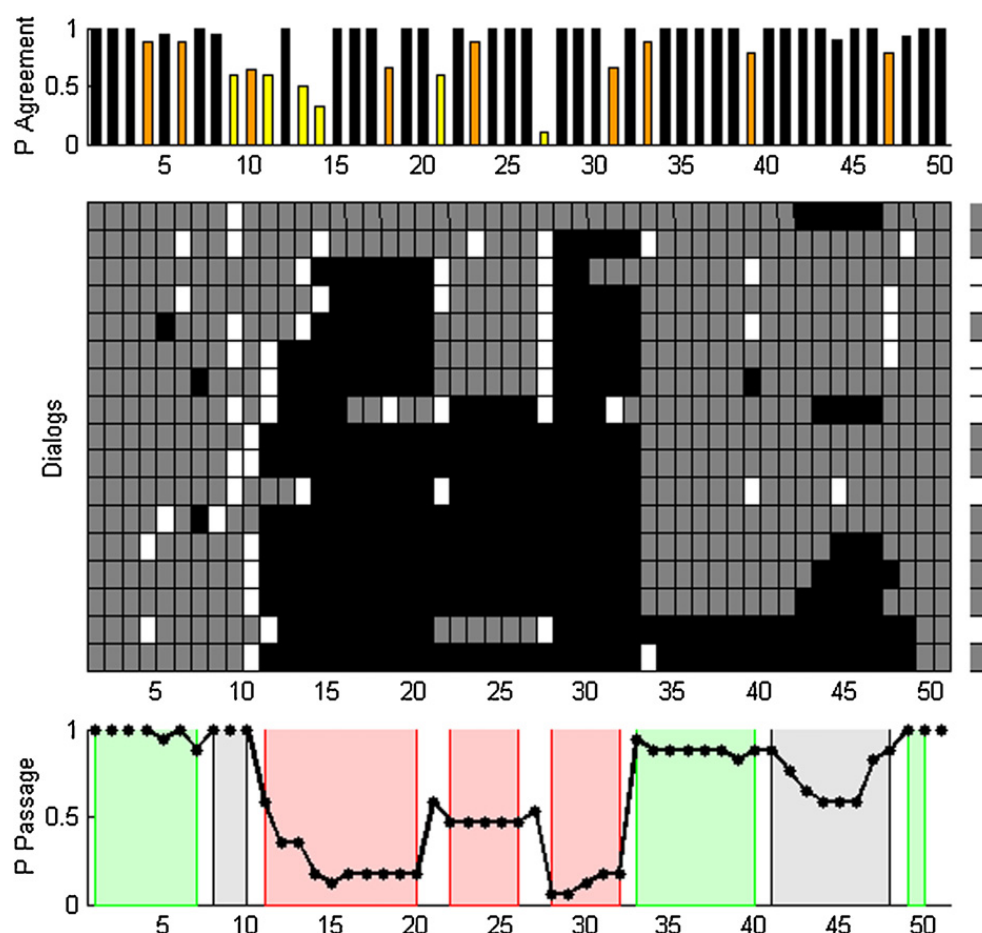


Fig. 2. (Top) $p(\text{Agreement})$ for all 50 questions. Questions showing major (yellow, $<60\%$) and minor (orange, $<33\%$) discrepancies between Socratic and experimental dialog are labeled. (Middle) Responses of all students. Each column corresponds to a question, each line indicates a student. White squares indicate discrepancies, black squares skips, and gray squares indicate agreement. Students were sorted according to the degree of average agreement. The rightmost column indicates whether students could (gray) or could not (white) transfer knowledge to a new square a few minutes after completion of the dialog. (Bottom) $p(\text{Passage})$ for all 50 questions, i.e. probability of responding (regardless of agreement) for each question (black line). Colored fields indicate distinct branches of the dialog (green, mandatory branches; red, conditional branches; gray, linear branches). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of the article.)

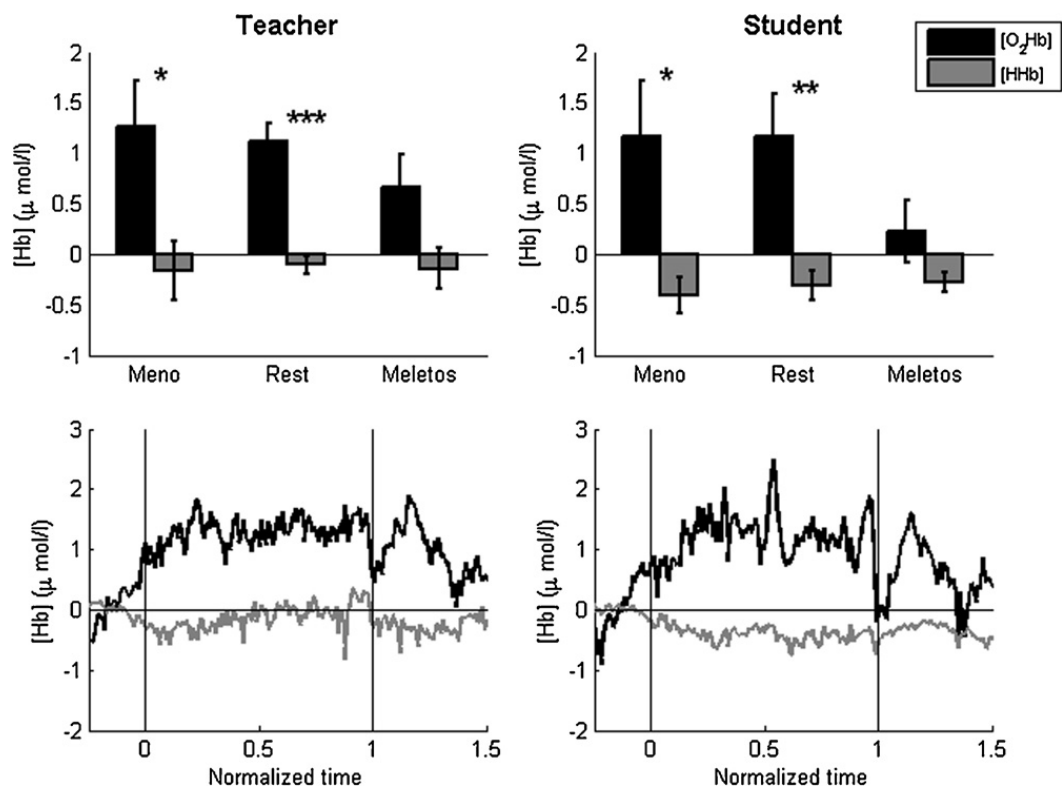


Fig. 3. Mean fNIRS activity. (top) Averaged responses of teachers (left) and students (right) for each particular period. Error bars correspond to standard errors of the means. Rest corresponds to a 2 min period after the dialog; * $p < 0.05$; ** $p < 0.01$; *** $p < 0.001$. (Bottom) Averaged time course in normalized time (0 and 1 correspond to beginning and end of all dialogs) are shown for teachers (left) and students (right). [O₂Hb]: dark gray; [HHb]: light gray.

to a virtually identical problem (only rescaled and presented immediately after the Meno dialog). In accordance with our previous observations, 41% of the participants failed to respond correctly. Hence, a key aspect for the following analysis of our neurophysiological data is whether it can be predictive of subsequent individual variability in generalization.

3.2. Effects of dialog's periods and averaged hemodynamic changes

We compared the averaged hemodynamic changes of [O₂Hb] and [HHb] of the whole Meno dialog duration as a block to the non-dialog periods, the rest period and the Meletos condition (Fig. 3 (top left and right)). Results showed an [O₂Hb] increase during the Meno dialog and rest periods as compared to the Meletos dialog condition, for both teachers and students. The time course of [O₂Hb] (Fig. 3 (bottom left and right)) reflects a sustained activation during Meno dialog which then fades out and peaks again in the rest period following this dialog.

To quantify and determine the statistical significance of these results we performed an ANOVA with the fixed factors 'concentration' ([O₂Hb] or [HHb]) and 'condition' (Rest, Meno, Meletos) (Table 1). The ANOVA revealed a main effect of

Table 1

ANOVA of averaged [O₂Hb] and [HHb] responses. Results are shown for [O₂Hb] and [HHb] responses with the fixed factors 'concentration' ([O₂Hb] or [HHb]) and 'condition' (Rest, Meno, Meletos). F -statistics with degree of freedom (F_x), significant values ($p \leq 0.05$) are highlighted (*).

ANOVA main effects teacher		
[O ₂ Hb]/[HHb]		$F_1 = 19.56, p < 0.001^{***}$
Rest/Meno/Meletos		$F_2 = 0.48, p = 0.62$
Interaction		$F_2 = 0.50, p = 0.61$
ANOVA main effects student		
[O ₂ Hb]/[HHb]		$F_1 = 15.36, p < 0.001^{***}$
Rest/Meno/Meletos		$F_2 = 0.83, p = 0.44$
Interaction		$F_2 = 1.18, p = 0.31$
Post hoc t -tests [O ₂ Hb] vs [HHb]		
Condition	Teacher	Student
	p -value	p -value
Meno	0.011*	0.010*
Rest	0.001***	0.006**
Meletos	0.077	0.201

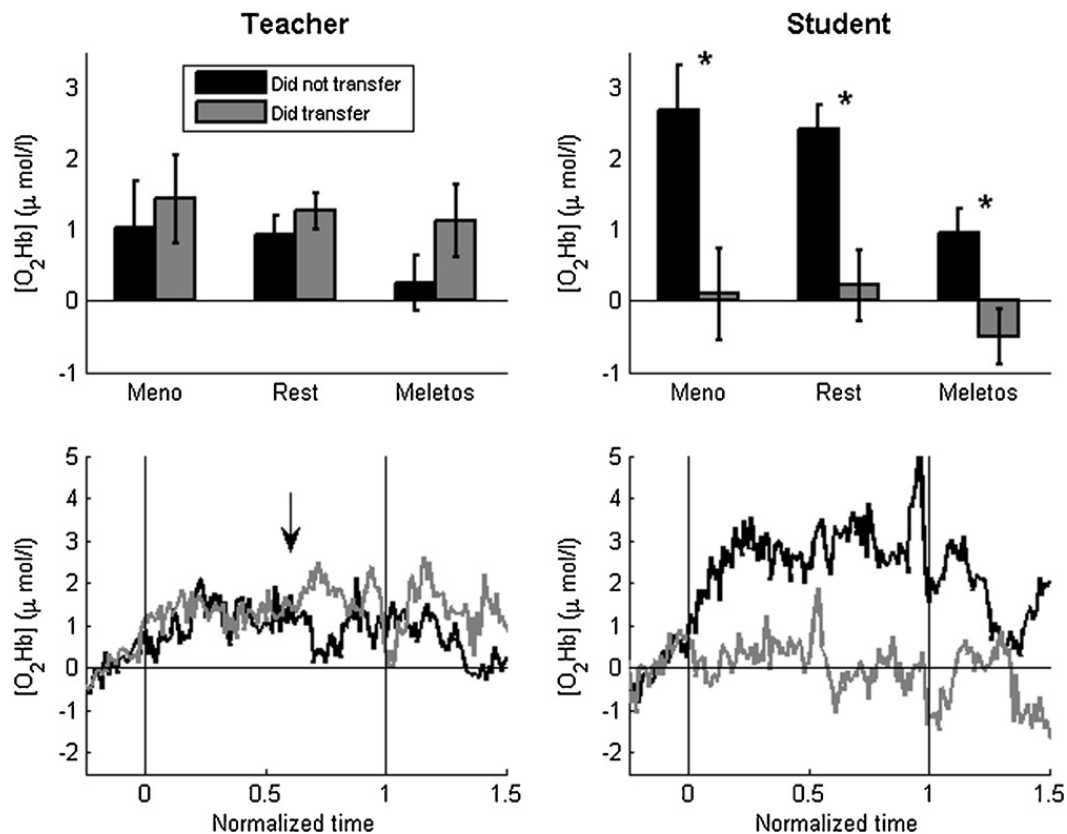


Fig. 4. Transfer modulates mean fNIRS activity. (Top) Averaged responses of $[O_2Hb]$ comparing dialogs in which students transferred (light gray) or did not transfer (dark gray) the learned knowledge (standard errors of dialog's means). Rest = 2 min period after dialog. (Bottom) Averaged time course in normalized time (0 and 1 correspond to beginning and end of all dialogs) are shown for teachers (left) and students (right). Arrow roughly corresponds to the normalized time of question 33.

'concentration' for both teachers and students. Post hoc comparisons showed that the $[O_2Hb]$ response was significantly larger during Meno dialog and rest as compared to the Meletos condition. There was no significant difference in the $[O_2Hb]$ or $[HHb]$ contrast in the rest period.

This previous analysis shows brain activity during Meno dialog, which persists with a slow inertia in the rest period following this dialog. Our next aim was to inquire whether these differences distinguish the group of students showing transfer from those who did not show transfer (Fig. 4). The results were quite revealing: teachers teaching students eliciting transfer, showed levels of activation comparable to those of teachers who participated in a Meno dialog in which the taught student did not show transfer (Fig. 4 (bottom and top left)). Instead, we observed a major increase in $[O_2Hb]$ activity for students who did not transfer compared to those who showed transfer: students that will later show generalization of knowledge showed a drop in activity during the whole Meno dialog, while students that could not generalize showed sustained levels of activity during the entire dialog (Fig. 4 (bottom and top right)). This finding was confirmed by ANOVA analysis using 'transfer' (yes or no) and 'condition' (Rest, Meno, Meletos) as independent factors. We performed independent ANOVAs for the $[O_2Hb]$ signal of students and teachers. Only the effect of 'transfer' on $[O_2Hb]$ activity of students was significant. Post hoc analysis revealed a significant difference between students showing transfer and those who did not in the three conditions (Rest, Dialog, Dialog II) (Table 2).

The dynamics of the $[O_2Hb]$ during the Meno dialog showed an interesting pattern. At about 60% of the dialog, we observe a discontinuity, revealing a small effect of student transfer in teachers NIRS signal, which did not reach significance. Interestingly, this phase of the dialog corresponds roughly to question number 33, when the crucial 'diagonal argument' – which is in the essence of the final line of reasoning – begins to be outlined.

Finally, we capitalized in the fact that students and teachers were recorded simultaneously. We inquired whether there was a correlation in average level of activity between teachers and students, averaging activity over the entire episodes (Rest, Meno, Meletos) (Table 3 and Fig. 5). We performed independent analysis for the group of students eliciting transfer and those who did not transfer. The results showed a very interesting interaction (Table 3 and Fig. 5 (top panel)): in the two dialogs (Meno and Meletos) for the group of students showing transfer we observed a positive correlation ($R^2 = 0.617$; $p > 0.058$ for Meno and $R^2 = 0.747$; $p > 0.088$ for Meletos dialogs) indicating that whenever a student showed greater activity (compared to the average of the student population) the teacher also showed greater levels of activity (relative to the average of the teacher population). The opposite effect was observed for the group of students who did not transfer, revealing a sort of

Table 2

ANOVA of averaged [O₂Hb] responses: transfer versus no-transfer. Results are shown for [O₂Hb] responses comparing students or teachers whose students had transferred or did not transfer the knowledge using fixed factors 'transfer' (yes or no) and 'condition' (Meno, Rest and Meletos). *F*-statistics with degree of freedom (*F*_{*x*}), significant values ($p \leq 0.05$) are highlighted (*).

ANOVA main effects teacher	
Transfer/no-transfer	$F_1 = 1.42, p = 0.241$
Rest/Meno/Meletos	$F_1 = 0.51, p = 0.605$
Interaction	$F_1 = 0.14, p = 0.873$
ANOVA main effects student	
Transfer/no-transfer	$F_1 = 19.18, p < 0.001^{***}$
Rest/Meno/Meletos	$F_1 = 2.34, p = 0.111$
Interaction	$F_1 = 0.47, p = 0.630$
Post hoc <i>t</i> -tests transfer vs no transfer	
Condition	Student
Meno	$p\text{-value}$
Rest	0.014*
Meletos	0.011*
	0.038*

decoupling, i.e. whenever the teacher showed greater activity, this was accompanied by a decrease in activity from the corresponding student in the dialog. Instead, during rest, activity was mostly decorrelated and teachers showed a significant decrease in the dispersion of activity relative to baseline.

To investigate whether this effect changed throughout Meno dialog, we measured correlations for both groups using the factor 'transfer' (yes or no) in sliding windows of 1% of the total duration of the Meno dialog (window size in absolute time was different for each student since the time of the dialog varied, see Section 2). The results were very consistent. Correlations were modest and non-significant in the beginning of the dialog. At about 60% of Meno dialog, in coincidence with the discontinuity observed in the average activity and corresponding to the critical moment of reasoning throughout the dialog, we observe that correlations become more significant revealing opposite effects: positive correlations for the group of students showing transfer and negative correlations for those who did not transfer.

4. Discussion

We present the first measure of brain activity in a teacher–student interaction. We relied on one of the most celebrated examples in pedagogy, the Meno dialog which has the virtue of producing a highly stereotyped educational trajectory. A second fundamental advantage is that this dialog elicits knowledge which can transfer beyond the specific context in about 50% of the students. We capitalized on this to investigate brain activity distinctively for educational experiences in which students later elicited transfer or not. From a purely behavioral point of view, these findings fully replicate these previous observation (Goldin et al., 2011), showing a remarkable reproducibility of the dialog, a persistence in the same types of errors made by the slave and a surprising lack of generalization.

This study is only a first step in a complex program to disentangle brain networks interacting in teacher–student interaction. Our brain measure, fNIRS has a great advantage of portability but at the expense of a relatively low spatial resolution. In fact, comparison across sensors did not show in this study any relevant information and were all pooled together as a single frontal channel. Hence, at this stage the specific connection of these observations to individual operations during the dialog are certainly very speculative and should be seen mainly as motivations for a full future program to disentangle them, relying on different neuroimaging tools to provide finer grain dynamics and topographical analysis to identify specific brain circuits.

We observed that both teachers and students exhibited significantly larger and positive [O₂Hb] changes during Meno dialog as compared to Meletos condition (Table 1 and Fig. 3). The positive [O₂Hb] responses found during Meno dialog were highly expected, since numerical/arithmetic processing, reasoning and more generally any task involving cognitive control

Table 3

Teacher–student activity correlations. Correlation coefficients and *p*-values are presented for the transfer and no-transfer conditions. PreQ33 and PostQ33 stands for the dialog periods previous or posterior to question 33, where the diagonal argument begins.

Condition	Transfer		No-transfer	
	R^2	<i>p</i> -value	R^2	<i>p</i> -value
Meno	0.617	0.058	−0.580	0.172
Rest	0.153	0.743	0.247	0.637
Meletos	0.747	0.088	−0.206	0.696
PreQ33	0.492	0.149	−0.410	0.362
PostQ33	0.649	0.042*	−0.692	0.085

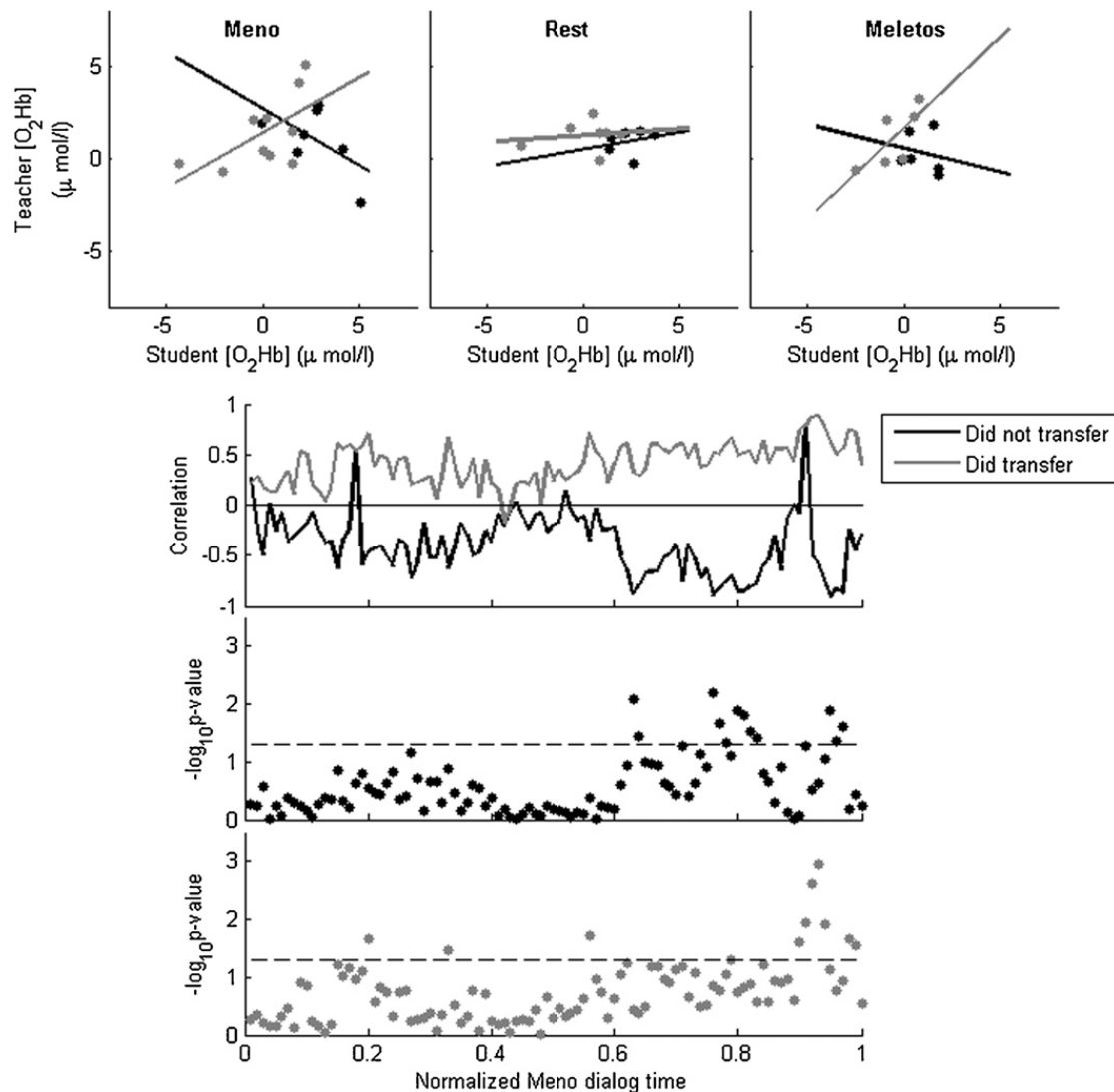


Fig. 5. Transfer reflected in [O₂Hb] between teacher and student. (Top) Averaged responses of [O₂Hb] for each teacher–student pair, for dialogs in which the student transferred (light gray dots) the learned knowledge or not (dark gray dots). Lines correspond to linear fits for both groups. (Bottom) Dialog time course (normalized time 0 and 1 correspond to the beginning and end of all dialogs) of the correlation coefficients separated for dialogs in which students transfer or did not transfer. Time course of the *p*-values are log-transformed. Dashed line corresponds to *p* = 0.05.

activates prefrontal cortices (Duncan, 2001; Duncan & Owen, 2000). Also, our findings are in line with previous fNIRS studies that have reported [O₂Hb] decreases during reading aloud (Fallgatter, Muller, & Strik, 1998; Liu, Borrett, Cheng, Gasparro, & Kwan, 2008; Wolf, Scholkmann, Rosenberger, Wolf, & Nelle, 2011). [O₂Hb] Activity persisted during the rest period. Although, at this stage we can only speculate about this persistent activity (compared to the Meletos condition) it may imply that the reasoning to which the dialog engages persist even after its explicit conclusion. Instead, the [HHb] remains virtually unchanged throughout the experiment.

More relevant for future studies is the fact that brain activity distinguishes the group of students who later elicit transfer (Table 2 and Fig. 4). Our main result showed a significant difference in prefrontal cortical activation between the students that could generalize the solution to any square in comparison to those that did not generalize at all (question 51). The former showed a minimum level of activation, similar to the teacher's brain pattern, while the latter maintained a higher activation. Also, students that later showed a sound transfer of knowledge showed a drop in activity during the whole dialog, whereas students that could not generalize showed sustained levels of activity during the entire dialog. As openly described above, at this point we can only speculate on the origin of this difference. Since prefrontal activity in fNIRS can be taken as a broad marker of mental effort (Duncan, 2001; Duncan & Owen, 2000; Sigman & Dehaene, 2008; Sigman et al., 2005; Zylberberg, Dehaene, Roelfsema, & Sigman, 2011) our results suggest that students who later showed transfer, achieve during Meno dialog a conceptual level of understanding which allows them to follow it without much effort (Vosniadou & Mason, 2012). This can be seen as an implicit measure of readiness for learning, similar to the observations of Goldin-Meadow and Wagner (2005), who could infer from gestures in counting tasks the predisposition for learning.

Another interesting finding was that specific brain activations during a giving lesson may predict the success of the learning process of the student; in other words we may predict the level of efficiency of the learning processes of an individual, in this case if the student can generalize or transfer the just acquired knowledge to other situation. In particular, we observed that activity is correlated in the group of teacher–students who result in an effective pedagogical experience but anti-correlated in the group of teacher–students in which the educational dialog fails; this effect was more pronounced in the moments of Meno dialog which are more relevant in terms of geometric reasoning. This finding shows that predictive markers of the efficacy of an educational dialog are measurable online throughout Meno dialog and moreover, that the level of the brain activity of the teacher may serve as a standard of efficiency for a given task. For interpretation of this observation we need to consider its many possible contributions. For instance, correlations may be induced by ostensive signals (Gergely, 2010), by gestures (Goldin-Meadow & Wagner, 2005), by signals denoting help seeking behavior (Roll, Alevén, McLaren, & Koedinger, 2011) – but overall it points to a principal concept in this dialog: successful interventions have comparable levels of activity between student and teacher. Instead, anti-correlated patterns of activity lead to unsuccessful interventions in which the student will not be able to transfer knowledge to a new situation.

In the last segment of the Socratic dialog, the teacher directs the student's attention to the diagonal of the square. At the key question 33, a new path in the geometrical reasoning is presented which leads toward the solution of the problem, a transition which we refer to as the 'diagonal argument'. At this critical moment, we observed a discontinuity revealing a small effect of student transfer in the teachers' fNIRS signal. In simple words, we observed that in successful interventions, at this critical moment of transmission of information, student and teachers 'dance at the same pace'. Although, this is at this stage a preliminary observation, which needs further experimentation, we can conclude that simultaneous measures of the teacher and pupil are necessary to understand the success or failure of education.

Taken together, a possible interpretation is that the geometric solution is correctly assimilated by the student only when the brain has reached a higher level of efficiency for this particular task, in other words 'doing more with less' neural activity (Battro, 2012). This increase in efficiency is what we see in the reduced level of brain activation of the teacher during the dialog. Instead, when the student is unable to generalize he or she still needs to sustain a higher level of neural activation. This is in line with recent observations showing an economy of functional brain networks (Bullmore & Sporns, 2012; Gallos, Makse, & Sigman, 2012; Gallos, Sigman, & Makse, 2012). We suggest that these costs can be reduced by a sound pedagogy that enhances the economy of the neural networks in place. We can expect that in the near future low-cost and high-performing wireless and portable brain imaging equipment will be common in experimental classroom settings and will, hopefully, help to transform the way we teach and learn.

5. Conclusion

This study demonstrates that reliable brain measures signaling relevant pedagogical variables (transfer) can be obtained in a realistic educational dialog. These results may pave the path for a program investigating brain activity in real educational setups where knowledge is acquired in a complex entangled process involving an interaction between a student and a teacher.

Disclosure statement

The authors have no conflict of interest.

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