MIND, BRAIN, AND EDUCATION

The Cognitive Neuroscience of the Teacher–Student Interaction

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ABSTRACT— Pedagogy is the science and art of teaching. Each generation needs to explore the history, theory, and practice of the teacher–student interaction. Here we pave the path to develop a science that explores the cognitive and physiological processes involved in the human capacity to communicate knowledge through teaching. We review examples from our previous work in this research area and discuss a path to reveal the cognitive and cerebral mechanisms by which we teach, unfolding a complex operation such as teaching in its constituents and components.

THE TEACHER–STUDENT INTERACTION

The dialogue between teacher and student is the core of pedagogy. In a sense, the history of education can be viewed as a progression and transformation of this basic interaction (Marrou, 1948). As recently discussed by Watanabe (2013), teaching may be often confused with simply one means of enhancing learning. Instead, Watanabe characterizes teaching as a dynamic phenomenon where interpersonal interactions occur explicitly and implicitly at multiple levels. Bonding through coordinated interpersonal interactions occupies a substantial portion of teaching. Moreover, as recently emphasized by Strauss and Ziv (2012), teaching is a natural cognitive ability in humans which develops following a well-defined path.

Cognitive neuroscience has progressively contributed a wealth of scientific knowledge to improve education, largely focused on the learner (Goldin et al., 2013; Lipina & Sigman, 2012). More generally, the neuroscience of how we learn has been a very active and prominent field of study (Gilbert, Sigman, & Crist, 2001). This enterprise has largely ignored the teacher perspective and the complex interaction which arises in the core educational dyad. We have proposed in other publications the need to reveal the cognitive and cerebral mechanisms by which we teach, unfolding a complex operation such as teaching in its constituents and components, as has been done with other domains of cognition such as attention (Petersen & Posner, 2012), mathematics (Dehaene, 2009), and theory of mind (Saxe, Carey, & Kanwisher, 2004). We have synthesized this effort, coining the term the "teaching brain," which is the title of this special series that brings together scientists and teachers to reconceptualize how we understand the phenomenon of teaching as an interaction. We suggest that combined cognitive psychology, neuroscience, and educational science should be investigated in teacher and student dialogues (Battro, 2010; Goldin, Pezzatti, Battro, & Sigman, 2011; Holper et al., 2013).

THE SOCRATIC DIALOGUE

We have paved the path in this direction with a first step capitalizing in what is probably the most famous educational dialogue described by Plato in *Meno*, a teacher–student interaction between Socrates and an illiterate slave (Crane, 2000). The choice to study this famous lesson of geometry by Socrates turned out to be of paramount importance, not only by its symbolic and historical importance in our Western civilization, but also because it has been recorded in extenso by Plato in such a way that it could be standardized and tested today in different cultures.

The Socratic dialogue is a lesson in geometry where the student learns (or, in the words of Plato, rather "discovers") how to double the area of a given square, which in essence is a demonstration of Pythagoras' theorem. We have standardized this dialogue in 50 questions and recorded the behavioral interaction in over 70 pairs of teachers and students during the spoken dialogue.

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In the first study (Goldin et al., 2011), we discovered a remarkable similarity of errors in the reasoning of contemporary students with those committed some 2400 years ago by the young slave of Meno. This has pertinence for basic science, speaking about universals in human reasoning. More relevant to educational practice, we discovered that nearly half the students, those who followed the dialogue more tightly without shortcutting questions with prior knowledge, failed to generalize, that is, to transfer the knowledge to a virtually identical situation—a square of a different size. These results questioned the efficacy of the Socratic dialogue, and suggested that only students with a scaffold of knowledge were the ones for whom the dialogue was successful. This led to a provocative hypothesis: students with no prior knowledge, those who are more engaged during the dialogue, are the ones achieving less generalization. We see this as a fruitful bridge between education (success of the dialogue), cognitive psychology (effect of prior knowledge on learning), and neuroscience (mental effort measures revealed by activity in the frontal cortex).

THE SOCRATIC DIALOGUE ASSESSED USING OPTICAL BRAIN IMAGING

In a second study using a hyperscanning setup based on functional near-infrared spectroscopy (fNIRS) (Holper et al., 2013), we examined the hemodynamic correlates of the Socratic dialogue. The study involved 17 pairs of subjects, in each session one representing the role of the teacher and the other the role of the student. During performance on the same version of Socratic dialogue used in our previous study (Goldin et al., 2011) we recorded both the student and the teacher simultaneously using wireless fNIRS sensors (Muehlemann, Haensse, & Wolf, 2008) over the prefrontal cortex. Owing to the relative high tolerance of the wireless fNIRS sensors to motion, subjects were allowed to move their hands, speak, and interact with each other. In addition, a control condition was included consisting of an approximately 10-min dialogue written on paper (Plato, 2008), which resembles the sort of responses, answers, and timing of the experimental dialogue. In this control dialogue, students and teachers were instructed to simply read aloud, each one taking over a part of this dialogue. Before and after the dialogues two rest periods (2 min each) were included as a baseline condition.

To assess the interaction between the teacher–student pairs during the experimental conditions as well as the transfer of knowledge, subsequent statistical analysis performed on the averaged prefrontal hemodynamic activity considered the factor "Transfer" (Yes versus No).

Our results showed two main findings. First, we observed that students who successfully transferred the knowledge showed smaller prefrontal hemodynamic responses during performance on the Socratic dialogue than those who did

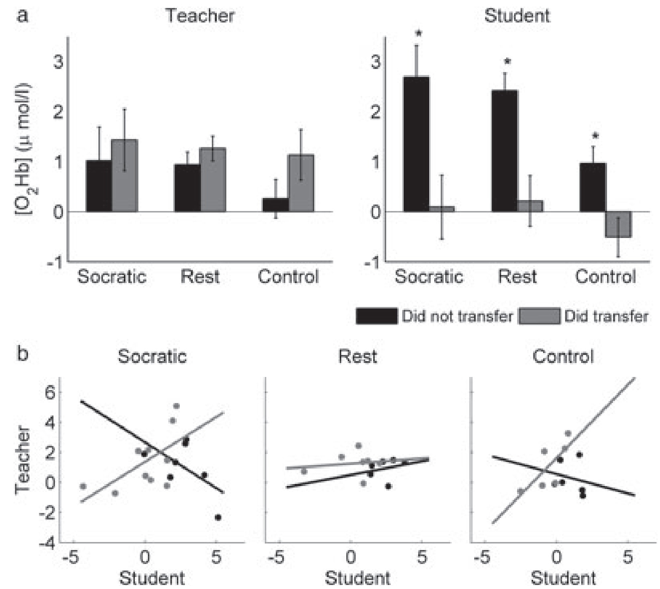

Fig. 1. Transfer reflected in averaged fNIRS activity. (a) Averaged hemodynamic responses (oxy-hemoglobin [O_2Hb]) comparing the groups in which students transferred (gray) or did not transfer (black) the learned knowledge (standard error of the mean). Rest = period after dialogue, Control = control dialogue. (b) Correlation of the averaged hemodynamic responses (oxy-hemoglobin [O_2Hb]) for each teacher–student pair, for the groups in which the student transferred (gray dots) the learned knowledge or not (black dots). Lines correspond to linear fits for both groups (After Holper et al., 2013).

not transfer. Figure 1a illustrates the differences in the hemodynamic response, distinguishing the groups in which students showed transfer from those who did not show transfer. In particular, these results showed that teachers teaching students eliciting transfer showed comparable levels of activation to those who taught students not eliciting transfer (Figure 1a, left). Hence, the hemodynamic activity of the teachers was not dependent on the transfer aspect. In contrast, students showed a remarkable different hemodynamic response depending on whether they could transfer or not. In particular, while students who did transfer of knowledge elicited significant lower levels of hemodynamic activity during the whole Socratic dialogue, students that could not transfer showed higher levels of activity during the entire dialogue (Figure 1a, right). In agreement with our prediction and closing the bridge, this indicated that those students with less prefrontal activity were the ones who showed more learning.

Moreover, above and beyond the main effect of reduced frontal activity, we considered the fact that students and teachers were recorded simultaneously. In particular, we investigated whether there was a correlation in the level of hemodynamic activity between teachers and students. The results demonstrated a strong positive correlation in activity between the students and the teachers in efficient educational dialogues (in which the student transferred the knowledge) (Figure 1b). In the same group of students a similar effect was found during the control dialogue, whereas during rest, activity was uncorrelated. These findings indicated 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, that is, a negative correlation indicating that whenever the teacher showed greater activity, this was accompanied by a decrease in activity from the corresponding student in the Socratic dialogue.

Second, we explored the temporal dynamics of the hemodynamic response during the Socratic dialogue. Figure 2 illustrates the time courses of both the averaged as well as the correlated hemodynamic activity. The averaged hemodynamics showed an interesting pattern. At about 60% of the dialogue, we observed a discontinuity, revealing a small (non-significant) effect of the students' transfers within the teachers' fNIRS signal (marked by the arrow in Figure 2a). This time point of the Socratic dialogue corresponds roughly to the question when the crucial "diagonal argument"—which is in the essence of the final line of reasoning (how to double a square)—begins to be outlined. Similarly, we investigated whether the correlation effect was consistent throughout the Socratic dialogue by calculating correlation coefficients for both groups in sliding windows of 1% of the total duration of the Socratic dialogue. The results were very consistent with what we observed in the average hemodynamic changes. Correlations were non-significant in the beginning of the dialogue (Figure 2b). At about 60% of Socratic dialogue, in coincidence with the discontinuity observed in the average activity and corresponding to the critical moment of reasoning throughout the dialogue, we observed that correlations became more significant revealing opposite effects: positive correlations for the group of students who did transfer and negative correlations for those who did not transfer. These results may indicate that a sort of cortical coupling between students and teachers is involved in successful educational interactions.

Taken together, the fNIRS study demonstrated that brain measures signaling relevant pedagogical variables (the transfer) can be obtained in a—though experimental—but realistic educational dialogue. On the basis of previous work (Rodriguez, 2013) that proposed by the structure of the human nervous system and its sensing, processing, and responding components as a framework for a reconceptualized teaching system, our results may pave the path for a program investigating brain activity in real educational setups where knowledge is acquired in complex processes involving the synchronistic interaction between teachers and students to achieve optimal teaching and learning experience.

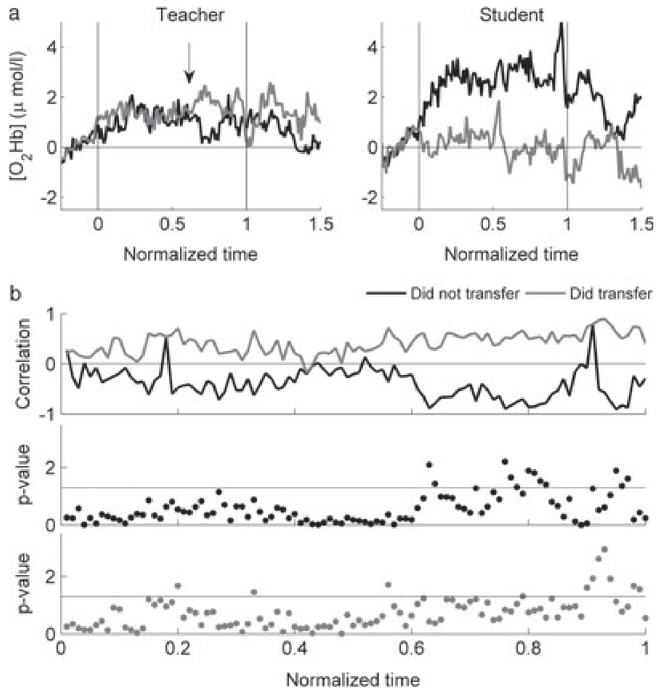

Fig. 2. Transfer reflected in temporal dynamics of fNIRS activity. (a) Averaged time course of the Socratic dialogue in normalized time (0 and 1 correspond to beginning and end of all dialogues) are shown for teachers and students separated for the groups in which students transfer (gray) or did not transfer (black). The arrow roughly corresponds to the normalized time of the question when the crucial "diagonal argument"—which is in the essence of the final line of reasoning (how to double a square)—begins to be outlined. (b) Socratic dialogue time course of the correlation coefficients in normalized time (0 and 1 correspond to the beginning and end of all dialogues). Time course of the *p*-values are log-transformed. Dashed line corresponds to $p = .05$ (After Holper et al., 2013).

TEACHING BRAIN CONSORTIUM

The opening sentences of the Socratic dialogue, a dialogue about virtue, are still engaging us into further questions concerning the origins of learning and the scope of teaching. Meno asked Socrates "whether virtue is acquired by teaching or practice; or if neither by teaching nor practice, then whether it comes to man by nature, or in what other way." Today the old alternative "teaching or practice" can be replaced by the pedagogy of "learning by doing" and the option of a "natural" acquisition of knowledge can be understood as the result of genetic and epigenetic processes. The Socratic dialogue was, as such, a pedagogical procedure with strong philosophical implications, like the theories of reminiscence that cannot be accepted without difficulty by modern science. Moreover, we have discovered that a classical Socratic dialogue has also serious limitations as a pedagogical method because it cannot ensure a stable cognitive acquisition at the end of the "lesson." The student may fail to generalize the cognitive procedure in a different setting (of course this failure on transfer of knowledge is common to other pedagogical methods too). To this observation regarding the behavior of the student we add, for the first time, the neurobiological component that may predict the success or failure of the whole lesson, but we need more research to understand this important fact. In this sense, considering all potential contributions from different research areas, we propose the idea of a *Teaching Brain Consortium*. In what follows, we discuss some important points in order to establish such a common platform that could support further explorations.

NEW PEDAGOGICAL ENVIRONMENTS

A key point of a *Teaching Brain Consortium* would be to establish bridges between the experimental laboratory and the classroom. It is important to develop a team work of scientists and teachers, which establishes the school as the place of choice for research in teaching and learning. The accelerated progress in mobile, wearable, and low-cost equipment of neurophysiology and brain imaging will reach the classroom soon, as did the information and communication technologies some two decades ago (Yano, 2013). Many schools today, for instance, have already implemented complex digital laboratories on robotics that may show the way to introduce brain research in a real pedagogical environment. Of course, this will raise some important ethical questions regarding privacy, among other concerns that should be taken into account (Lopez-Rosenfeld, Goldin, Lipina, Sigman, & Fernandez Slezak, 2013).

The Socratic dialogue described above constitutes an example of how education and neuroscience can be bridged. It is very important to be aware, as identified in John Bruer's seminal paper (Bruer, 1997), whether observation of brain activity adds substantial additional information relevant for educational practice, or if instead (as in the majority of the cases as demonstrated by Bruer) it merely serves to ground ideas established by cognitive psychology which are relevant to basic neuroscience but not to education.

NEW METHODS OF ASSESSMENT

A second point that could be addressed by a *Teaching Brain Consortium* would be the development, evaluation, and introduction of new methods of assessments in the classroom. In common practice the fact that we can establish the difference between learning and understanding may suffice to evaluate the student. The important novelty, however, is that with a careful monitoring of brain activity of both student and teacher we could predict above chance which student will fail or succeed in the generalization test (Holper et al., 2013). This is totally new information based on the evidence of scientific records. It is certainly not a kind of "lie detector"; the student is perfectly convinced of the truth of his or her sayings in both cases, but the brain images offer a "plus" that is hidden to everyone and not detectable by the common test. This is similar to the information that can be obtained by analyzing gestures that students do with their hands when they talk, which is typically not consciously accessible and yet provides an early sign that the speaker is ready to learn a particular task (Broaders, Wagner Cook, Mitchell, & Goldin-Meadow, 2007). Our example is very modest, but we think it is compelling enough to inform about a failure or a success. We can imagine in the future that new kinds of tests based on brain imaging will add evidence to assess the quality of the learning process, as we did in our case with the generalization test.

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