HOW TO IMPROVE NEUROSCIENCE EDUCATION FOR THE PUBLIC AND FOR A MULTI-PROFESSIONAL AUDIENCE IN DIFFERENT PARTS OF THE GLOBE

EDITED BY: Analía Arévalo, Guilherme Lepski and Valeria Abusamra
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Topic Editors:
Analía Arévalo, University of Sao Paulo Medical School, Brazil
Guilherme Lepski, University of São Paulo, Brazil
Valeria Abusamra, University of Buenos Aires, Argentina

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Lutz Jäncke,
University of Zurich, Switzerland

*CORRESPONDENCE
Analía Arévalo
analia.l.arevalo@gmail.com

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Editorial: How to improve neuroscience education for the public and for a multi-professional audience in different parts of the globe

Analía Arévalo[1]*, Valeria Abusamra[2,3] and Guilherme Lepski[1,4]

[1]Department of Experimental Surgery, Medical School, University of São Paulo, São Paulo, Brazil, [2]National Scientific and Technical Research Council (CIIPME/CONICET), Buenos Aires, Argentina, [3]Department of Linguistics, University of Buenos Aires, Buenos Aires, Argentina, [4]Department of Neurosurgery, Eberhard Karls University, Tübingen, Germany

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Editorial on the Research Topic
How to Improve Neuroscience Education for the Public and for a Multi-Professional Audience in Different Parts of the Globe

Recent years have seen a growing interest in brain and neuroscience-related knowledge, both among laypeople and those working in critical areas such as health and education. The last decades have also seen an explosion in mass-produced information, as well as the advent of the infamous fake news. In several countries, the search for (and almost parallel supply of) neuroscience-related courses has grown exponentially, but the rate at which this has happened almost guarantees that quality does not match quantity. Another area of rapid growth, especially in North America and Europe, has been the industry of brain-based products, mostly pseudoscientific endeavors that target parents, teachers, schools, and even local governments.

Why is this so important? Neuroscience knowledge—but more importantly—the critical thinking and research skills required to search for and comprehend primary information sources, can help individuals make the right decision regarding their own health and wellbeing. For people in the health industry, it can mean offering the right treatment for their patients. For people in journalism and communication, this can mean translating scientific findings to a lay audience in an easy to understand and accurate way. Finally, for people in education, it can mean properly guiding and preparing generations to come, as well as contributing to the proper allocation of resources.

The gap between cognitive neuroscience and learning is still very conspicuous. And one of the consequences of this distance is the appearance and propagation of myths that in many cases have some scientific support.

Studies conducted in several countries converge on the finding that neuroscience-related knowledge is generally poor among people in all fields, including educators, and in some studies in Europe and South America, it was even observed that heightened interest in neuroscience and even exposure to some short introductory courses actually predicts (paradoxically) a greater belief in neuromyths, combined with an inability to judge information as being real or pseudoscientific. It seems that simply adding quick neuroscience courses to education curricula or in other fields may not be enough to remedy the problem.

The solution may lie in a combination of methods, including courses that specifically cover field-related neuromyths and provide skills that go beyond the content taught, as well as regular, consistent training and access to reliable sources of information. More importantly, this effort requires that neuroscience educators communicate effectively with professionals in various disciplines, including psychologists, health professionals, and educators in other fields.

In this Special Topic, we gathered contributions from researchers in eight countries and four continents who presented original experiments, opinion pieces and descriptions of applied programs that all aim to improve neuroscience-related knowledge in their own corner of the world.

In "*What does the general public know (or not) about neuroscience? Effects of age, region and profession in Brazil*," Arévalo et al. gathered information about neuroscience-related knowledge among laypeople in Brazil living in all five regions and working in several different fields. The results of the survey filled a gap in knowledge about the largest country in South America, as most previous surveys were conducted in the US, Europe, and Spanish-speaking countries in Latin America. The study revealed overall high neuromyth endorsement, especially among respondents from regions with lower income levels and more limited access to education and the internet, as well as older people. Interestingly, people working in the health field did not perform better than those working in the humanities or exact sciences, revealing poor overall training of professionals in areas that would benefit most from such knowledge. The authors question the quality of the myriad neuroscience courses offered online or at institutions and suggest ways of improving such course offerings.

A response to this problem was offered by Ivanova et al., in "*Advancing neurolinguistics in Russia: experience and implications of building experimental research and evidence-based practices*," who described their establishment of the Center for Language and Brain at HSE University in Moscow, which started as a small group of scientists and in a short amount of time became a center for cutting edge research and several public outreach programs.

Two other studies conducted in Brazil used fNIRS to study learning in younger students as well as online learning efficiency. Barreto et al. analyzed the interaction between preschool students and their teachers as a way of predicting efficient learning ("*A new statistical approach for fNIRS hyperscanning to predict brain activity of preschoolers' using teacher's*"), while Oku and Sato analyzed an online learning environment in order to outline possible methodological improvements to be implemented ("*Predicting student performance using machine learning in fNIRS data*").

Another study from Portugal and two from the UK reveal that educators may need some help in this process as well. Through a survey of initial teacher training courses and the availability of brain-related books for educators, Rato et al. reveal the urgent need for developing training curricula for future kindergarten and elementary school teachers in Portugal ("*Looking for the brain inside the initial teacher training and outreach books in Portugal*"). In a perspective article ("*The Learning Styles neuromyth is still thriving in medical education*") and systematic review ("*How common is belief in the Learning Styles neuromyth, and does it matter? A pragmatic systematic review*"), Newton et al. and Newton and Salvi reveal the widespread endorsement of the Learning Styles neuromyth among educators in different areas despite no empirical evidence for it and discuss the implications of this belief on education.

So, what can be done to aide teachers in this process? In "*On neuroeducation: why and how to improve neuroscientific literacy in educational professionals*," Jolles and Jolles present a proposal that includes four themes of neuroscience content "that every teacher should know." The authors emphasize the need for interdisciplinary involvement in such efforts. Also, in "*Teaching the science in neuroscience to protect from neuromyths: from courses to fieldwork*," Carboni et al. describe a set of activities being conducted in Uruguay since 2013 that aim to bridge the gap between Education and Neuroscience and involve activities that bring together educators and scientists to work on research projects, as well as a course that focuses on the applications of Neuroscience to Education. These authors emphasize the need to provide educators with a deeper understanding of the science to make their own better educational decisions. In "*Neuroscience concepts changed teachers' views of pedagogy and students*" (Chang et al.), an educational neuroscience concepts course offered a group of K-12 teachers in Texas a lens to reconsider, re-envision and re-design their lessons. Two other innovative studies were conducted with educators in Liberia: in one, training in neuroscience and mental health development improved teacher self-efficacy, self-responsibility for student outcomes, and motivation to teach ("*Tiered neuroscience and mental health professional development in Liberia improves teacher self-efficacy, self-responsibility, and motivation*," Brick et al.), and in the other, mental health training improved teachers' understanding of their students' mental and emotional difficulties, reduced their use of verbal and corporal punishment, and helped them establish positive rewards systems ("*Training-of-trainers neuroscience and mental* *health teacher education in Liberia improves self-reported support for students*," Brick et al.). And in an effort to improve teaching neuroscience history, Schleim offers a new perspective on the classic case of Phineas Gage ["*Neuroscience education begins with good science: communication about Phineas Gage (1823-1860), one of neurology's most-famous patients, in scientific articles*"].

Finally, in "*Neuroscience outside the box: from the laboratory to discussing drug abuse at schools*," Machado do Vale et al. offer perspectives on how scientists can engage educators, students, policymakers, and the public at large to effect real change in society through a neuroscientific perspective.

The aim of this collection of 14 articles was to join forces with a large network of neuroscience and education professionals and inspire and guide others with similar interests toward effective solutions. Forging strong links between domains requires double literacy: teachers need to become "neuroscientifically literate" and neuroscientists have to become "educationally literate."

We hope these and future work can continue to improve neuroscience education for the public and for a multi-professional audience around the globe.

Author contributions

All authors listed have made a substantial, direct, and intellectual contribution to the work and approved it for publication.

Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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SYSTEMATIC REVIEW
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How Common Is Belief in the Learning Styles Neuromyth, and Does It Matter? A Pragmatic Systematic Review

Philip M. Newton* and Atharva Salvi

Swansea University Medical School, Swansea University, Swansea, United Kingdom

A commonly cited use of Learning Styles theory is to use information from self-report questionnaires to assign learners into one or more of a handful of supposed styles (e.g., Visual, Auditory, Converger) and then design teaching materials that match the supposed styles of individual students. A number of reviews, going back to 2004, have concluded that there is currently no empirical evidence that this "matching instruction" improves learning, and it could potentially cause harm. Despite this lack of evidence, survey research and media coverage suggest that belief in this use of Learning Styles theory is high amongst educators. However, it is not clear whether this is a global pattern, or whether belief in Learning Styles is declining as a result of the publicity surrounding the lack of evidence to support it. It is also not clear whether this belief translates into action. Here we undertake a systematic review of research into belief in, and use of, Learning Styles amongst educators. We identified 37 studies representing 15,405 educators from 18 countries around the world, spanning 2009 to early 2020. Self-reported belief in matching instruction to Learning Styles was high, with a weighted percentage of 89.1%, ranging from 58 to 97.6%. There was no evidence that this belief has declined in recent years, for example 95.4% of trainee (pre-service) teachers agreed that matching instruction to Learning Styles is effective. Self-reported use, or planned use, of matching instruction to Learning Styles was similarly high. There was evidence of effectiveness for educational interventions aimed at helping educators understand the lack of evidence for matching in learning styles, with self-reported belief dropping by an average of 37% following such interventions. From a pragmatic perspective, the concerning implications of these results are moderated by a number of methodological aspects of the reported studies. Most used convenience sampling with small samples and did not report critical measures of study quality. It was unclear whether participants fully understood that they were specifically being asked about the matching of instruction to Learning Styles, or whether the questions asked could be interpreted as referring to a broader interpretation of the theory. These findings suggest that the concern expressed about belief in Learning Styles may not be fully supported by current evidence, and highlight the need to undertake further research on the objective *use* of matching instruction to specific Learning Styles.

Keywords: evidence-based education, pragmatism, neuromyth, differentiation, VARK, Kolb, Honey and Mumford

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Robbert Smit,
University of Teacher Education St. Gallen, Switzerland

Reviewed by:
Håvard Lorås,
Norwegian University of Science and Technology, Norway
Steve Wininger,
Western Kentucky University, United States
Kristen Betts,
Drexel University, United States

****Correspondence:***
Philip M. Newton
p.newton@swansea.ac.uk

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INTRODUCTION

For decades, educators have been advised to match their teaching to the supposed Learning styles of students (Hyman and Rosoff, 1984). There are now over 70 different Learning Styles classification systems (Coffield et al., 2004). They are largely questionnaire-based; students are asked to self-report their preferences for different approaches to learning and other activities and are then assigned one or more Learning Styles. The VARK classification is perhaps the most well-known (Newton, 2015; Papadatou-Pastou et al., 2020), which categorizes individuals as one or more of Visual, Auditory, Read-Write and Kinesthetic learners. Other common Learning Styles classifications in the literature include those by Kolb, Honey and Mumford, Felder, and Dunn and Dunn (Coffield et al., 2004; Newton, 2015).

In the mid-2000s two substantial reviews of the literature concluded that there was currently no evidence to support the idea that the matching of instructional methods to the supposed Learning Styles of individual students improved their learning (Coffield et al., 2004; Pashler et al., 2008). Subsequent reviews have reached the same conclusion (Cuevas, 2015; Aslaksen and Lorås, 2018) and there have been numerous, carefully controlled attempts to test this "matching" hypothesis (e.g., (Krätzig and Arbuthnott, 2006; Massa and Mayer, 2006; Rogowsky et al., 2015, 2020; Aslaksen and Lorås, 2019). The identification of supposed student Learning Style does not appear to influence the way in which students choose to study (Husmann and O'Loughlin, 2018), and does not correlate with their stated preferences for different teaching methods (Lopa et al., 2015).

Despite this lack of evidence, a number of studies suggest that many educators believe that matching instruction to Learning Style(s) is effective. One of the first studies to test this belief was undertaken in 2009 and looked at various statements about the brain and nervous system which are widespread but which are not supported by research evidence, for example the idea what we only use 10% of our brain, or that we are born with all the brain cells that we will ever have. The study described such statements as "neuromyths" and showed that belief in them was high, including belief in matching of instruction to Learning Styles which was reported by 82% of a sample of trainee teachers in the United Kingdom (Howard-Jones et al., 2009). A number of similar studies have been conducted since, and have reached the same conclusion, with belief in Learning Styles reaching as high as 97.6% in a study of preservice teachers in Turkey (Dündar and Gündüz, 2016).

This apparent widespread belief in an ineffective teaching method has caused concern amongst the education community. Part of the concern arises from a perception that the use of Learning Styles is actually harmful (Pashler et al., 2008; Riener and Willingham, 2010; Dekker et al., 2012; Rohrer and Pashler, 2012; Dandy and Bendersky, 2014; Willingham et al., 2015). The proposed harms include concerns that learners will be pigeonholed or demotivated by being allocated into a Learning Style. For example, a student who is categorized as an "auditory learner" may conclude that there is no point in pursing studies, or a career, in visual subjects such as art, or written subjects such as journalism and so be demotivated during those classes. They might also conclude that they will be more successful in auditory subjects such as music, and thus inappropriately motivated by unrealistic expectations of success and become demotivated if that success does not materalise. It is worth noting however that many advocates of Learning Styles propose that it may be motivating for individual learners to know their supposed style (Coffield et al., 2004). Another concern is that to try and match instruction to Learning Styles risks wasting resources and effort on an ineffective method. Educators are motivated to try and do the best for their learners, and a logical extension of the matching hypothesis is that educators would need to try and generate 4 or more versions of their teaching materials and activities, to match the different styles identified in whatever classification they have used. Additional concerns are that the continued belief in Learning Styles undermines the credibility of educators and education research, and creates unwarranted and unrealistic expectations of educators (Newton and Miah, 2017). These unrealistic expectations could also manifest when students do not achieve the academic grades that they expect, or do not enjoy, or engage with, their learning; if students are not taught in a way that matches their supposed Learning Style, then they may attribute these negative experiences to a lack of matching and be further demotivated for future study. These concerns, and controversy, have also generated publicity in the media, both the mainstream media and in publications focused on educators (Pullmann, 2017; Strauss, 2017; Brueck, 2018).

The apparent widespread acceptance of a technique that is not supported by evidence is made more striking by the fact that there are many teaching methods which demonstrably promote learning. Many of these methods are simple and easy to learn, for example the use of practice tests, or the spacing of instruction (Weinstein et al., 2018). These methods are based upon an abundance of research which demonstrates how we learn (and how we don't), in particular the limitations of human working memory for the processing of new information in real time, and the use of strategies to account for those limitation (e.g., Young et al., 2014). Unfortunately these evidence-based techniques do not appear to be reflected in teacher-training textbooks (National Council on Teacher Quality, 2016).

The lack of evidence to support the matching hypothesis is now acknowledged by some proponents of Learning Styles theory. For example Richard Felder states in a 2020 opinion piece

> "*As the critics of learning styles correctly claim, the meshing hypothesis (matching instruction to students' learning styles maximizes learning) has no rigorous research support, but the existence and utility of learning styles does not rest on that hypothesis and most proponents of learning styles reject it.*" (Felder, 2020)

and

> "*I now think of learning styles simply as common patterns of student preferences for different approaches to instruction, with certain attributes - behaviors, attitudes, strengths, and weaknesses - being associated with each preference*". (Felder, 2020)

This specific distinction between the matching/meshing hypothesis, and the existence of individual preferences, is at the heart of many studies which have examined belief in the matching hypothesis. Many studies ask about both preferences and matching. These are very different concepts, but the wording of the questions asked about them is very similar. Here for example is the original wording of the questions used in Howard-Jones et al. (2009), which has been used in many studies since. Participants are asked to rate their agreement with the statements that;

> "*Individuals learn better when they receive information in their preferred learning style (e.g., auditory, visual, kinesthetic)*" (**Matching question**).

and, separately,

> "*Individual learners show preferences for the mode in which they receive information (e.g., visual, auditory, kinesthetic)*" (**Preferences question).**

The similarities between these statements creates a risk that participants may not fully distinguish between them. This risk is heightened by the existence of similar-sounding but distinct concepts. For example there is evidence that individuals show fairly stable differences in certain cognitive tests, e.g., of visual or verbal ability, sometimes called a "cognitive style" (e.g., Mayer and Massa, 2003). There is also evidence that individuals express reasonably stable preferences for the way in which they receive information, although these preferences do not appear to be correlated with abilities (Massa and Mayer, 2006). This literature, and the underlying science, is complex and multi-faceted, but the nomenclature bears a resemblance to the literature on Learning Styles and the science itself may be the genesis of many Learning Styles theories (Pashler et al., 2008).

This potential overlap in concepts is reflected in studies which have examined what educators understand by the term Learning Styles. A 2020 qualitative study investigated this in detail and found a range of different interpretations of the term Learning Styles. Although the VAK/VARK classification system was the most commonly recognized classification, many educators incorrectly conflated it with other theories, such as Howard Gardeners theory of Multiple Intelligences, and learning theories such as cognitivism. There was also a large diversity in the ways in which educators attempted to account for the use of Learning Styles in their teaching practice. Many educators responded by including a diversity of approaches within their teaching, but not necessarily mapped onto specific Learning Styles instrument or with instruction specific to individuals. For example using a wide variety of audiovisual modalities, or a diversity of active approaches to learning (Papadatou-Pastou et al., 2020). An earlier study reported that participants incorrectly used the term "Learning Styles" interchangeably with "Universal Design for Learning," and other strategies that take into account individual differences (differentiation) (Ruhaak and Cook, 2018). This complexity is reflected in teacher-training textbooks, which commonly refer to Learning Styles but in a variety of ways, including student motivation and preferences for learning (Wininger et al., 2019). There is also a related misunderstanding about Learning Styles theory; the absence of evidence for a matching hypothesis does not mean that students should all be taught the same way, or that they do not have preferences for how they learn. Attempts to refute the matching hypothesis have been incorrectly interpreted in this way (Newton and Miah, 2017).

Thus, one interpretation of the current literature and surrounding media is that, concern has arisen due to widespread belief in the efficacy of an ineffective and potentially harmful teaching technique, but the participants in studies which report on this widespread belief do not clearly understand what they are being asked, or what the intended consequences are if they disagree with what they are asked.

One set of questions to be addressed in this review then is whether the aforementioned concern is fully justified, and whether this potential confusion is reflected in the data. We examine this by using a systematic review approach to take a broader look at trends and patterns in a larger dataset. The evidence showing a lack of evidence for matching instruction to Learning Styles has been available since 2004. It would be reasonable then to expect that belief in this method would have declined since then, particularly if it is harmful. A related question is whether educators actually *use* Learning Styles; to generate multiple versions of teaching materials and activities would require considerable additional effort for no apparent benefit, which should also hasten the decline of Learning Styles.

With this is mind, we have conducted a Pragmatic Systematic Review. Pragmatism is an approach to research that attempts to identify results that are useful, relevant to practical issues in the real-world, rather than focusing solely on academic questions (Duram, 2010; Feilzer, 2010). Pragmatic Evidence-based Education is an approach which combines the most useful education research evidence and relies on judgement to apply it in specific context (Newton et al., accepted). Thus, here we have designed research questions to help us develop and discuss findings which are, we hope, useful to the sector rather than solely of academic interest. In addition, we have included many of the usual measures of study quality associated with a systematic review. However, these are included as results as in themselves, rather than as reasons to include/exclude studies from the review. A detailed picture of the quality of studies should be useful for the sector to determine whether the findings justify the aforementioned concern, and whether it needs to be addressed.

Research Questions

1. What percentage of educators believe in the matching of instruction to Learning Styles?
2. What percentage of educators enact, or plan to enact the matching of instruction to Learning Styles?
3. Has belief in matching instruction to Learning Styles decreased over time?
4. Do evidence-based interventions reduce belief in matching instruction to Learning Styles?
5. Do studies present clear evidence that participants understand the difference between (a) matching instruction

to Learning Styles and (b) preferences exhibited by learners for the ways in which they receive information?

METHODS

The review followed the PRISMA guidelines for conducting and reporting a Systematic Review (Moher et al., 2009), with a consideration of measures of quality and reporting for survey-based research, taken from (Kelley et al., 2003; Bennett et al., 2011).

Eligibility Criteria, Information Sources, and Search Strategy

Education research is often published in journals that are outside the immediate field of education, but instead are linked to the subject being learned. Therefore, we used EBSCO to search the following databases: CINAHL Plus with Full Text; eBook Collection (EBSCOhost); Library, Information Science & Technology Abstracts; MEDLINE; APA PsycArticles; APA PsycINFO; Regional Business News; SPORTDiscus with Full Text; Teacher Reference Center; MathSciNet via EBSCOhost; MLA Directory of Periodicals; MLA International Bibliography. We also searched PubMed and the Education Research database ERIC.

The following search terms were used: "belief in learning styles"; "believe in learning styles"; "believed in learning styles"; "Individuals learn better when they receive information in their preferred learning style" (this is the survey question used in the original Howard-Jones paper (Howard-Jones et al., 2009). Neuromyth*; "learning styles" AND myth AND survey or questionnaire. We used advanced search settings for all sources to apply related words and to ensure that the searches looked for the terms within the full text of the articles. No date restriction was applied to the searches and so the results included items up to and including April 2020.

This returned 1,153 items. Exclusion of duplicates left 838 items. These were then screened according to the inclusion criteria (below). Screening articles on the basis of their titles identified 85 eligible items. The abstracts of these were then evaluated which resulted in 46 items for full-text screening. We also used Google Scholar to search for the same terms. Google Scholar provides better inclusion of non-journal research including of gray literature (Haddaway et al., 2015) and unpublished theses that are hosted on servers outside the normal databases (Jamali and Nabavi, 2015). For example, when searching for the specific survey item used in the original Howard-Jones paper (Howard-Jones et al., 2009) and in many studies subsequently; "Individuals learn better when they receive information in their preferred learning style." This search returned zero results on ERIC and four result on PsychINFO, but returned 107 results on Google Scholar, most of which were relevant. However, all Google Scholar results had to hand screened in real-time since Google Scholar does not have the same functionality as the databases described above; it includes multiple versions of the same papers, and the search interface is limited, making it difficult to accurately quantify and report search results (Boeker et al., 2013).

Study Selection

To be included in the review a study had to meet the following criteria;

- Survey educators about their belief in the matching of instruction to one or more of the Learning Styles classifications identified in aforementioned reviews (Coffield et al., 2004; Pashler et al., 2008) and/or educators use of that matching in their teaching. This included pre-service or trainee teachers (individuals studying toward a teaching qualification).
- Report sufficient data to allow calculation of the number and percentage of respondents stating a belief that individuals learn better when they receive information in their preferred learning style (or use/plan to use Learning Styles theory in this way).

Exclusion criteria included the following

- Surveys of participant groups that were not educators or trainee educators.
- Only survey belief in individual learning preferences (i.e., rather than matching instruction).
- Survey other opinions about Learning Styles, for example whether they explain differences in academic abilities (e.g., Bellert and Graham, 2013).
- Survey belief in personalizing learning to suit preferences or other characteristics not included in the Learning Styles literature (e.g., prior educational achievement, "deep, surface or strategic learners."

Some studies were not explicitly clear that they surveyed belief in *matching* instruction, but used related non-specific concepts such as the "existence of Learning Styles." These were excluded unless additional information was available to confirm that the studies specifically surveyed belief in matching instruction to Learning Styles. For example (Grospietsch and Mayer, 2018) reported surveying belief in the existence of Learning Styles. However, the content of this paper discussed knowledge acquisition in the context of matching, and stated that the research instruments was derived from Dekker et al. (2012), and had been used in an additional paper by the same authors (Grospietsch and Mayer, 2019), while a follow-up paper from the same authors described both these earlier papers as surveying belief in matching instruction to Learning Styles (Grospietsch and Mayer, 2020). These two survey studies were therefore included. Another study (Canbulat and Kiriktas, 2017) was not clear and no additional information was available. Two emails were sent to the corresponding author with a request for clarity, but no response was received.

Application of the inclusion criteria resulted in 33 studies being included, containing a total of 37 samples. We then went back to Google Scholar to search within those articles which cited the 33 included studies. No further studies were identified which met the inclusion criteria.

Data Collection Process

Data were independently extracted from every paper by two authors working separately (PN + AS). Extracted data were then compared and any discrepancies resolved through discussion.

Data Items

The following metrics were collected where available (all data are shown in **Appendix 1**):

- The year the study was published
- Year that data were collected (where stated, and if different from publication date. If a range was stated, then the year which occupied the majority of the range was taken (e.g., Aug 2014–April 2015 was recorded as 2014).
- Country where the research was undertaken
- Publication type (peer reviewed journal, thesis, gray literature)
- Population type (e.g., academics in HE, teachers, etc.)
- Whether or not funding was received and if so where from
- Whether or not a Conflict of Interest was reported/detected
- Target population size
- Sample size
- "N" (completed returns)
- Average teaching experience of participant group
- Percentage and number of participants who stated agreement with a question regarding belief in the matching of instruction to Learning Styles, and the text of the specific question asked
- Percentage and number of participants who stated agreement with a question regarding belief that learners express preferences for how they receive information, and the text of the specific question asked
- The percentage and number of participants who stated that they did, or would, *use* matching to instruction in their teaching, and the text of the specific question asked
- The percentage and number of participants who stated agreement with a question regarding belief in the matching of instruction to Learning Styles after any intervention aimed at helping participants understand the lack of evidence for matching instruction to Learning Styles

Summary Measures and Synthesis of Results

Most measures are simple percentages of participants who agreed, or not, with questionnaire statements. Summary measures are then the average of these. In order to account for unequal sample size, simple weighted percentages were calculated; percentages were converted to raw numbers using the stated "N" for an individual sample. The sum of these raw numbers from each study was then divided by the sum of "N" from each study and converted to a percentage. Percentages from individual studies were used as individual data points in groups for subsequent statistical analysis, for example to compare the percentage of participants who believed in matching instruction to the percentage who actually used Learning Styles in this way.

Risk of Bias Within and Across Studies

Bias is defined as anything which leads a review to "over-estimate or under-estimate the true intervention effect" (Boutron et al., 2019). In this case an "intervention effect" would be belief in, or use of, Learning Styles either before or after any intervention, or belief in a preference for receiving information in different ways.

Many concerns regarding bias are unlikely to apply here. For example, publication bias, wherein results are less likely to be reported if they are not statistically significant. Most of the data reported in the studies under consideration here are not subject to tests of significance, so this is less of a concern.

However, a number of other factors affect can generate bias within a questionnaire-type study of the type analyzed here. These factors also affect the external validity of study findings, i.e., how likely is it that study findings can be generalized to other populations. We collected the following information from each study in order to assess the external validity of the studies. These metrics were derived from multiple sources (Kelley et al., 2003; Bennett et al., 2011; Boutron et al., 2019). Some were calculated from the objective data described above, whereas others were subject to judgement by the authors. In the latter case, each author made an independent judgement and then any queries were resolved through discussion.

- **Sampling Method**. Each study was classified into one of the following categories. Categories are drawn from the literature (Kelley et al., 2003) and the studies themselves.
    - *Convenience* sampling. The survey was distributed to all individuals within a specified population, and data were analyzed from those individuals who voluntarily completed the survey.
    - *Snowball* sampling. Participants from a convenience sample were asked to then invite further participants to complete the survey.
    - *Unclassifiable*. Insufficient information was provided to allow determination of the sampling method
    - (no other sampling approaches were used by the included studies)
- **Validity Measures**
    - **Neutral Invitation**. Were participants invited to the study using neutral language. Neutrality in this case was defined as not demonstrating support for, or criticism of, Learning Styles in a way that could influence the response of a participant. An example of a neutral invitation is Dekker et al. (2012) *"The research was presented as a study of how teachers think about the brain and its influence on learning. The term neuromyth was not mentioned in the information for teachers."*
    - **Learning Styles vs. styles of learning**. Was sufficient information made available to participants for them to be clear that they were being asked about Learning Styles rather than styles of learning, or preferences (Papadatou-Pastou et al., 2020). For example, was it explained that, in order to identify a Learning Style, a questionnaire needs to be administered which then results in learners being

allocated to one or more styles, with named examples (e.g., Newton and Miah, 2017).

- **Matching Instruction**. If yes to above, was it also made clear that, according to the matching hypothesis, educators are supposed to tailor instruction to individual learning styles.

Additional Analyses

The following additional analyses were pre-specified in line with our initial research questions.

Has Belief in Matching Instruction to Learning Styles Decreased Over Time?

The lack of evidence to support matching instruction to Learning Styles has been established since the mid-2000s and has been the subject of substantial publicity. We might therefore hypothesize that belief in matching instruction has decreased over time, for example due to the effects of the publicity, and/or from a revision of teacher-training programmes to reflect this evidence. Three different analyses were conducted to test for evidence of a decrease.

1. A Spearman Rank Correlation test was conducted to test for a correlation between the year that the study was undertaken and the percentage of participants who reported a belief in matching instruction to learning styles. A significant negative correlation would indicate a decrease over time.
2. Belief in matching instruction to Learning Styles was compared in trainee teachers vs. practicing teachers. If belief in Learning Styles was declining then we would expect to see lower rates of belief in trainee teachers. Two samples (Tardif et al., 2015; van Dijk and Lane, 2018) contained a mix of trainee and qualified teachers and were excluded from this analysis. The samples of teachers in Dekker et al. (2012) and Macdonald et al. (2017) both contained 94% practicing teachers and 6% trainee teachers, and so the samples were counted as practicing teachers for the purpose of this analysis.
3. A Spearman Rank Correlation test was conducted to test for a correlation between the average teaching experience of study participants and the percentage of participants who reported a belief in matching instruction to Learning Styles. If belief in matching instruction to learning styles is decreasing then we might expect to see a negative correlation.

Is There a Difference Between Belief in Learning Styles and Use of Learning Styles

The weighted percentage for each of these was calculated, and the two groups of responses were also compared.

Question Validity Analysis

In many of the studies here, participants were asked about both "preferences for learning" and "matching instruction to Learning Styles." As described in the introduction, the wording for both questions was similar. If there was confusion about the difference between these two statements, then we would expect the pattern of response to them to be broadly similar. To test for this, we calculated a difference score for each study by subtracting the percentage of participants who believed in matching instruction to Learning Styles from the percentage who agreed that individuals have preferences for how they learn. We then conducted a one-tailed t-test to determine whether the distribution of these scores was significantly different from zero. We also compared both groups of responses.

Analysis

All datasets were checked for normal distribution before analysis using a Kolmogorov-Smirnov test. Non-parametric tests were used where datasets failed this test. Individual tests are described in the results section.

RESULTS

89.1% of Participants Believe in Matching Instruction to Learning Styles

34/37 samples reported the percentage of participants who stated agreement with an incorrect statement that individuals learn better when they receive information in their preferred learning style. The simple average of these 34 data points is 86.2%. To calculate a weighted percentage, these percentages were converted to raw numbers using the stated "N." The sum of these raw numbers was then divided by the sum of "N" from the 34 samples to create a percentage. This calculation returned a figure of 89.1%. A distribution of the individual studies is shown in **Figure 1**.

No Evidence of a Decrease in Belief Over Time

As described in the methods we undertook three separate analyses to test for evidence that belief in Learning Styles has decreased over time. (1) A Spearman Rank correlation analysis was conducted to test for a relationship between the year a study was conducted and the percentage who reported that they believed in matching instruction to Learning Styles. No significant relationship was found ($r = -0.290$, $P = 0.102$). (2) Belief in matching instruction to Learning Styles was compared in samples of qualified teachers ($N = 16$) vs. pre-service teachers ($N = 12$) using a Mann-Whitney U test. No significant difference was found (**Figure 2**). A Mann Whitney U test returned a P value of 0.529 (U = 82). When calculating the weighted percentage from each group, belief in matching was 95.4% for pre-service teachers and 87.8% for qualified teachers. The weighted percentage for participants from Higher Education was 63.6%, although this was not analyzed statistically since these data were calculated from only three studies and these were different to the others in additional ways (see Discussion). (3) A Spearman Rank correlation analysis was conducted to test for a relationship between the mean years of experience reported by a participant group (qualified teachers) and the percentage who reported that the believed in matching instruction to Learning Styles. No significant relationship was found ($r = -0.158$, $P = 0.642$).

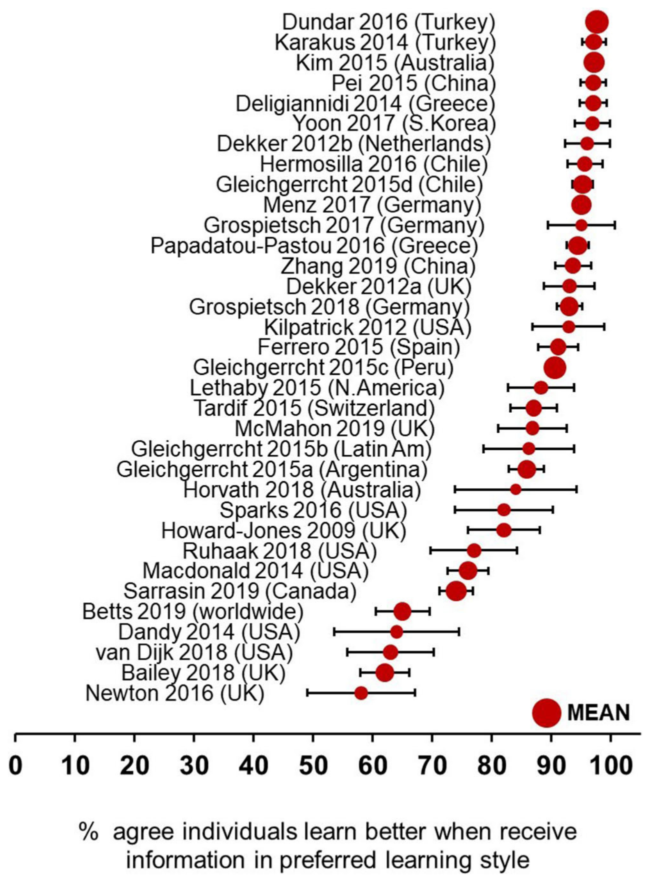

FIGURE 1 | The percentage of participants who stated agreement that individuals learn better when they receive information in their preferred Learning Style. Individual studies are shown with the name of the first author and the year the study was undertaken. Data are plotted as ±95% CI. Bubble size is proportional to the Log10 of the sample size.

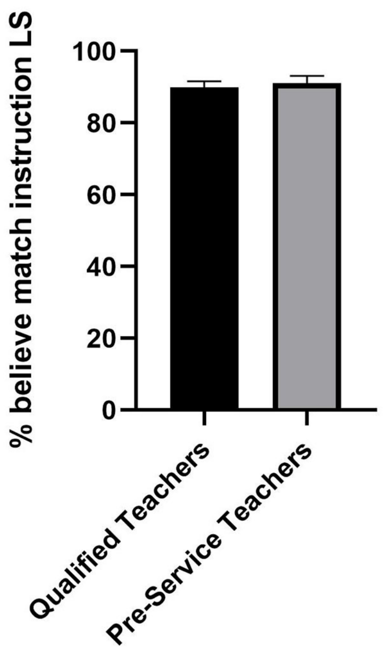

FIGURE 2 | No difference between the percentage of Qualified Teachers vs. Pre-Service Teachers who believe in the efficacy of matching instruction to Learning Styles. The percentage of educators who agreed with each statement was compared by Mann-Whitney U test. $P = 0.529$.

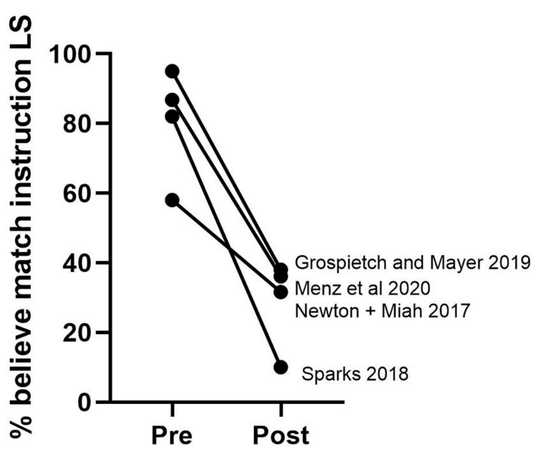

FIGURE 3 | Interventions which explain the lack of evidence to support the efficacy of matching instruction to Learning Styles are associated with a drop in the percentage of participants who report agreeing that matching is effective. Each of the four studies used a pre-post design to measure self-reported belief. The weighted percentage dropped from 78.4 to 37.1%.

Effect of Interventions

Four studies utilized some form of training for participants, to explain the lack of current evidence for matching instruction to Learning Styles. A pre-post test analysis was used in these studies to evaluate participants belief in the efficacy of matching instruction to Learning Styles both before and after the training. Calculating a weighted percentage revealed that, in these four studies, belief went from 78.4 to 37.1%. The effect size for this intervention effect was large (Cohens $d = 3.6$). Comparing these four studies using a paired t-test revealed that the difference between pre and post was significant ($P = 0.012$). Results from the individual studies are shown in **Figure 3**.

Use of Learning Styles vs. Belief

Seven studies measured self-report of use, or planned use, of matching instruction to Learning Styles. Calculating the weighted average revealed that 79.7% of participants said they used, or intended to use, the matching of instruction to Learning Styles. This was compared to the percentage who reported that they believed in the efficacy of matching instruction. A Mann-Whitney U test was used since four of the seven studies did not measure belief in matching to instruction and so a paired test was not possible. No significant difference was found between the percentage of participants who reported believing that matching instruction to Learning Styles is effective (89.1%), and the percentage who used, or planned to use, it as a teaching method (79.7%) ($P = 0.146$, $U = 76.5$). Data are shown in **Figure 4**.

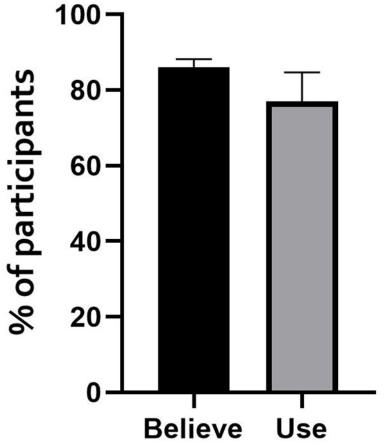

FIGURE 4 | No difference between the percentage of participants who report believing in the efficacy of matching instruction to Learning Styles, and the percentage who used, or intended to use, Learning Styles in this way. The pooled weighted percentage was 89.1 vs. 79.7%. $P = 0.146$ by Mann-Whitney U test.

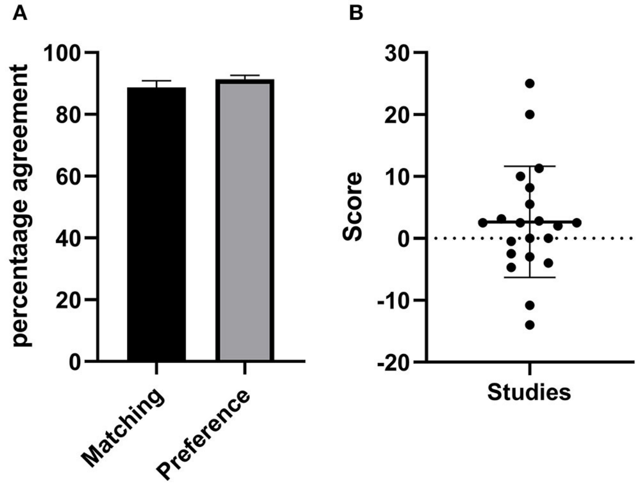

FIGURE 5 | No difference between belief in Learning Styles and Learning Preferences. **(A)** The percentage of participants who report believing that individuals have preferences for how the receive information, and the percentage who report believing that individuals learn better when receiving information in their preferred Learning Style. **(B)** The difference between these two measures, calculated for individual samples. A negative score means that fewer participants believed that students have preferences for how they received information compared to the percentage who believed that matching instruction to Learning Styles is effective.

No Difference in Belief in Preferences vs. Belief in Matching Instruction to Learning Styles

As described in the introduction, many studies compared belief in matching instruction to Learning Styles (a "neuromyth") with a correct statement that individuals show *preferences* for the mode in which they receive information. Twenty-one studies questioned participants on both their belief in matching instruction to Learning Styles, and their belief that individual learners have preferences for the ways in which they receive information. A Wilcoxon matched-pairs test showed no significant difference between these two datasets ($P = 0.262$, $W = 57$). A difference score was calculated by subtracting the percentage who believe in matching instruction from the percentage who believe that learners show preferences. The mean of these scores was 2.66, with a Standard Deviation of 8.97. A one sample t-test showed that the distribution of these scores was not significantly different from zero ($P = 0.189$). The distribution of these scores is shown in **Figure 5** and reveals many negative scores, i.e., where belief in matching instruction to Learning Styles is higher than a belief that individuals have preferences for how they receive information.

Risk of Bias and Validity Measures

A summary table of the individual studies is shown in **Table 1**. (The full dataset is available in **Appendix 1**).

Of the 34 samples which measured belief in matching instruction to Learning Styles, 30 of them used the same question as used in Howard-Jones et al. (2009) (see Introduction). The four which used different questions were "Does Teaching to a Student's Learning Style Enhance Learning?" (Dandy and Bendersky, 2014), "Students learn best when taught in a manner consistent with their learning styles" (Kilpatrick, 2012), "How much do you agree with the thesis that there are different learning styles (e.g., auditory, visual or kinesthetic) that enable more effective learning?" (Menz et al., 2020) and "A pedagogical approach based on such a distinction favors learning" (participants had been previously been asked to rate their agreement with the statement "Some individuals are visual, others are auditory") (Tardif et al., 2015).

Sampling

Thirty of the 37 samples included used convenience sampling. Three of the studies used snowballing from convenience sampling, while the remaining 4 were unclassifiable; these were all from one study whose participants were recruited *"at various events related to education (e.g., book fair, pedagogy training sessions, etc.), by word of mouth, and via email invitations to databases of people who had previously enquired about information/courses on neuroscience and education"* (Gleichgerrcht et al., 2015). Thus, no studies used a rigorous, representative, random sample and so no further analysis was undertaken on the basis of sampling method. Some studies considered representativeness in their methodology, for example Dekker et al. (2012) reported that the local schools they approached "*could be considered a random selection of schools in the UK and NL*" but the participants were then *"Teachers who were interested in this topic and chose to participate."* No information is given about the size of the population or the number of individuals to whom the survey was sent, and no demographic characteristics are given regarding the population.

TABLE 1 | Characteristics of included studies.

First Auth	Yr published	Country	Yr of study	Population type	Neutral invitation?	Make clear LS?	Make clear matching?	Sampling Method	N	Ave teaching exp	HJQ?	% Believe matching	% post training	% Use LS	% preference
Betts	2019	Worldwide	2019	Higher Education	–	N	N	Sno	427	–	Y	65	–	–	90
Bailey	2018	UK + Ireland	2017	Sports Coaches	–	N	N	Con	545	–	Y	62	–	–	–
Carter	2015	Australia	2015	Pre-service teachers	–	Y	Y	Con	235	0	–	–	–	95.3	–
Dandy	2014	USA	2014	Higher Education	–	Y	Y	Con	81	–	N	64	–	–	–
Dekker	2012	UK	2012	Teachers (mixed)	Y	N	N	Con	137	–	Y	93	–	–	95
Dekker	2012	Netherlands	2012	Teachers (mixed)	Y	N	N	Con	105	–	Y	96	–	–	82
Deligiannidi	2015	Greece	2014	Teachers (mixed)	–	N	N	Con	217	15.1	Y	97	–	–	97
Dundar	2016	Turkey	2016	Pre-service teachers	–	N	N	Con	2932	0	Y	97.6	–	–	86.8
Ferrero	2016	Spain	2015	Teachers (mixed)	Y	N	N	Con	284	16.9	Y	91.1	–	–	93.6
Gleichgerrcht	2015	Argentina	2015	Teachers (mixed)	–	N	N	Unc	551	17.8	Y	85.8	–	–	94
Gleichgerrcht	2015	Latin America	2015	Teachers (mixed)	–	N	N	Unc	80	17.8	Y	86.2	–	–	97.5
Gleichgerrcht	2015	Peru	2015	Teachers (mixed)	–	N	N	Unc	2222	17.8	Y	90.6	–	–	96.1
Gleichgerrcht	2015	Chile	2015	Teachers (mixed)	–	N	N	Unc	598	17.8	Y	95.2	–	–	97.7
Grospietsch	2019	Germany	2018	Pre-service teachers	Y	N	N	Con	550	0	Y	93	–	–	93
Grospietsch	2017	Germany	2017	Pre-service teachers	–	N	N	Con	57	0	Y	95	38	–	–
Hermosilla	2016	Chile	2016	Pre-service teachers	Y	N	N	Con	184	0	Y	95.6	–	–	98.4
Horvath	2018	UK, USA, Australia	2018	Teachers	–	N	N	Con	50	18.6	Y	84	–	–	94
Howard-Jones	2009	UK	2009	Pre-service teachers	–	N	N	Con	158	0	Y	82	–	–	79
Karakus	2014	Turkey	2014	Teachers (mixed)	–	N	N	Con	278	–	Y	97.1	–	–	94.6
Kilpatrick	2012	USA	2012	Teachers (Elem School)	–	N	N	Con	70	13.4	N	92.9	–	84.3	
Kim	2017	Australia	2015	Pre-service teachers	–	N	N	Con	1144	0	Y	97.1	–	–	–
Lethaby	2015	North America	2015	Teachers (TESOL)	–	N	N	Con	128	–	Y	88.3	–	–	91.41
Macdonald	2017	USA	2014	Teachers (mixed)	–	N	N	Con	598	–	Y	76	–	–	–
McMahon	2019	UK	2015	Pre-service teachers	–	N	N	Con	130	–	Y	86.8	63.1	–	–
Menz	2020	Germany	2017	Pre-service teachers	Y	N	N	Sno	936	0	N	95.0	–	–	–
Morehead	2015	USA	2015	Higher Education	Y	N	N	Con	146	0	–	–	–	77	91
Newton	2016	UK	2016	Higher Education	Y	Y	Y	Con	114	11	Y	58	31.6	33	–
Papadatou-Pastou	2017	Greece	2016	Pre-service teachers	–	N	N	Con	571	0	Y	94.4	–	–	93.9
Pei	2015	East China	2015	Teachers (mixed)	–	N	N	Con	238	–	Y	97	–	–	93
Piza	2019	USA	2017	Higher Education	–	N	N	Con	156	–	–	–	–	79.4	91
Ruhaak	2018	USA	2018	Pre-service teachers	–	N	N	Con	129	0	Y	77	–	90	79.5
Sarrasin	2019	Quebec	2019	Teachers (mixed)	–	N	N	Con	972	4	Y	74	–	–	–
Sparks	2018	USA	2016	Pre-service teachers	–	N	N	Con	84	0	Y	82	10	–	–
Tardif	2015	Switzerland	2015	Teachers + Pre-service	–	N	N	Con	274	–	N	87	–	80	–
van Dijk	2018	USA	2018	Teachers + Pre-service	–	N	N	Sno	169	–	Y	63	–	–	83
Yoon	2018	South Korea	2017	Pre-service teachers	Y	N	N	Con	132	0	Y	96.9	–	–	–
Zhang	2019	China	2019	Teachers (Headmasters)	–	N	N	Con	251	18.8	Y	93.6	–	–	88.9

For sampling, Con = Convenience, Sno = Snowball, Unc = unclassifiable. HJQ = Did the study measure use the question from Howard-Jones et al. (2009) to measure belief in matching instruction to Learning. Make clear LS did the study provide additional information to explain to participants about Learning Styles before surveying their belief in matching instruction to Learning Styles. Make clear matching. Did the study did the study provide additional information to explain to participants about the specific issue of matching instruction to Learning Styles, before surveying participants on their belief in that topic.

Response Rate

Only five samples reported the size of the population from which the sample was drawn, and so no meaningful analysis of response rate can be drawn across the 37 samples. In one case (Betts et al., 2019) the inability to calculate a response rate was due to our design rather than the study from which the data were extracted; Betts et al. (2019) reported distributing their survey to a Listserv of 65,780, but the respondents included many non-educators whose data were not relevant for our research question. It is perhaps worth noting however that their total final participant number was 929 and so their total response rate across all participant groups was 1.4%

Neutral Invitation

Nine of the 37 studies presented evidence of using a neutral invitation. None of the remaining studies provided evidence of a *biased* invitation; the information was simply not provided.

Briefing on Learning Styles and Matching

Two of the 37 studies reported giving participants additional information regarding Learning Styles, sufficient (in our view) for participants to be clear that they were being asked specifically about Learning Styles as defined by Coffield et al., and the matching on instruction to Learning Styles.

DISCUSSION

We find that 89.1% of 15,045 educators, surveyed from 2009 through to early 2020, self-reported a belief that individuals learn better when they receive information in their preferred Learning Style. In every study analyzed, the majority of educators reported believing in the efficacy of this matching, reaching as high as 97.6% in one study by Dundar and colleagues, which was also the largest study in our analysis, accounting for 19% of the total sample (Dündar and Gündüz, 2016).

Perhaps the most concerning finding from our analysis is that there is no evidence that this belief is decreasing, despite research going back to 2004 which demonstrates that such an approach is ineffective and potentially harmful. We conducted three separate analyses to test for evidence of a decline but found none, in fact the total percentage of pre-service teachers who believe in Learning Styles (95.4%) was higher than the percentage of qualified teachers (87.8%). This finding suggests that belief in matching instruction to Learning Styles is acquired before, or during, teacher training. Tentative evidence in support for this is a preliminary indication that belief in Learning Styles may be lower in educators from Higher Education, where teacher training is less formal and not always compulsory. In addition, Van Dijk and Lane report that overall belief in neuromyths is lower in HE although they do not report this breakdown for their data on Learning Styles (van Dijk and Lane, 2018). However, the studies from Higher Education are small, and two of them are also studies where more information is provided to participants about Learning Styles (see below).

From our pragmatic perspective, there are a number of issues to consider when determining whether these findings should be a cause for alarm, and what to do about them.

The data analyzed here are mostly extracted from studies which assess teacher belief in a range of so-called neuromyths. These all use some version of the questionnaire developed by Howard-Jones and co-workers (Howard-Jones et al., 2009). The value of surveying belief in neuromyths has been questioned, on the basis that, in a small sample of award-winning teachers, there did not appear to be any correlation between belief in neuromyths and receiving a teaching award (Horvath et al., 2018). The Horvath study ultimately proposed that awareness of neuromyths is "irrelevant" to determining teacher effectiveness and played down concerns, expressed elsewhere in the field, that belief in neuromyths might be harmful to learners, or undermine the effectiveness of educators. We have only analyzed one element of the neuromyths questionnaire (Learning Styles), but we share some of the concerns expressed by Horvath and co-workers. The majority (30/34) of the samples analyzed here measured belief in Learning Styles using the original Howard-Jones/Dekker questionnaire. A benefit of having the same questions asked across multiple studies is that there is consistency in what is being measured. However, a problem is that any limitations with that instrument are amplified within the synthesis here. One potential limitation with the Howard-Jones question set is that the "matching" question is asked in many of the same surveys as a "belief" question, as shown in the introduction, potentially leading participants to conflate or confuse the two. Any issues may then be exacerbated by a lack of consistency in what participants understand by "matching instruction to Learning Styles"; this could affect all studies. The potential for multiple interpretations of these questions regarding Learning Styles is acknowledged by some authors (e.g., Morehead et al., 2016), and some studies report a lack of clarity regarding the specific meaning of Learning Styles and the matching hypothesis (Ruhaak and Cook, 2018; Papadatou-Pastou et al., 2020). This lack of clarity is reflected also in the psychometric properties of Learning Styles instruments themselves, with many failing to meet basic standards of reliability and validity required for psychometric validation (Coffield et al., 2004). In addition, we have previously founds that participants, when advised against matching instruction to Learning Styles, may conclude that this means educators should eliminate any consideration of individual preferences or variety in teaching methods (Newton and Miah, 2017).

Here we found no significant differences between participant responses to the question regarding belief in matching instruction vs. the question about individual preferences, with almost half the studies analyzed actually reporting a higher percentage of participants who believed in matching instruction when compared to belief that individuals have preferences for how they receive information. This is concerning from a basic methodological perspective. The question is normally thus; "*Individual learners show preferences for the mode in which they receive information (e.g., visual, auditory, kinesthetic).*" In any sample of learners, some individuals are going to express preferences. It may not be all learners, and those preferences may not be stable for all learners, and the question does not encompass all preferences, but the question, as asked, cannot be anything other than true.

More relevant for our research questions is the apparent evidence of a lack of clarity within the research instrument; it may not be clear to study participants what the matching hypothesis is and so it is difficult to conclude that the results truly represent belief in matching instruction to Learning Styles. This finding is tentatively supported by our analysis which shows that, in the two studies which give participants additional instructions and guidance to help them understand the matching hypothesis, belief in matching instruction to Learning Styles is much lower, a weighted average of 63.5% (Dandy and Bendersky, 2014; Newton and Miah, 2017). However, these are both small studies, and both are conducted in Higher Education rather than school teaching, so the difference may be explained by other factors, for example the amount and nature of teacher-training given to educators in Higher Education when compared to school-teaching. It would be informative to conduct further studies in which more detail was provided to participants about Learning Styles, before they are asked whether or not they believed matching instruction to Learning Styles is effective.

However, even if we conclude that the findings represent, in part, a lack of clarity over the specific meaning of "matching instruction to Learning Styles," this might itself still be a cause for concern. The theory is very common in teacher training and academic literature (Newton, 2015; National Council on Teacher Quality, 2016; Wininger et al., 2019) and so we might hope that the meaning and use of it is clear to a majority of educators. An additional potential limitation is that the Howard-Jones question cites VARK as an example of Learning Styles, when there are over 70 different classifications. Thus we have almost no information about belief in other common classifications, such as those devised by Kolb, Honey and Mumford, Dunn and Dunn etc. (Coffield et al., 2004).

79.7% of participants reported that they used, or planned to use, the approach of matching instruction to Learning Styles. This high percentage was surprising since our earlier work (Newton and Miah, 2017) showed that only 33% of participants had used Learning Styles in the previous year. If Learning Styles are ineffective, wasteful of resources and even harmful, then we might predict that far fewer educators would actually use them. There are a number of caveats to the current results. There are only seven studies which report on this and all are small, accounting for <10% of the total sample. Most are not paired, i.e., they do not explicitly ask about belief in the efficacy of Learning Styles and then compare it to use of Learning Styles. The questions are often vague, broad and do not specifically represent an example of matching instruction to individual student Learning Styles as organized into one of the recognized classifications. For example "do you teach to accommodate those differences" (Learning Styles). Agreement with statements like these might reflect a belief that educators feel like they have to say they use them in order to respect any/all individual differences, rather than Learning Styles specifically. In addition this is still a self-report of a behavior, or planned behavior. It would be useful, in further work, to measure actual behavior; how many educators have actually designed distinct versions of educational resources, aligned to multiple specific individual student Learning Styles? This would appear to be a critical question when determining the impact of the Learning Styles neuromyth.

The studies give us little insight into *why* belief in Learning Styles persists. The theory is consistently promoted in teacher-training textbooks (National Council on Teacher Quality, 2016) although there is some evidence that this is in decline (Wininger et al., 2019). If educators are themselves screened using Learning Styles instruments as students at school, then it seems reasonable that they would then enter teacher-training with a view that the use of Learning Styles is a good thing, and so the cycle of belief would be self-perpetuating.

We have previously shown that the research literature generally paints a positive picture of the use of Learning Styles; a majority of papers which are "about" Learning Styles have been undertaken on the basis that matching instruction to Learning Styles is a good thing to do, regardless of the evidence (Newton, 2015). Thus an educator who was unaware of, or skeptical of, the evidence might be influenced by this. Other areas of the literature reflect this idea. A 2005 meta-analysis published in the *Journal of Educational Research* attempted to test the effect of matching instruction to the Dunn and Dunn Learning Styles Model. The results were supposedly clear;

> "*results overwhelmingly supported the position that matching students' learning-style preferences with complementary instruction improved academic achievement*" (Lovelace, 2005).

A subsequent publication in the same journal in 2007 (Kavale and LeFever, 2007) discredited the 2005 meta-analysis. A number of technical and conceptual problems were identified with the 2005 meta-analysis, including a concern that the vast majority of the included studies were dissertations supervised by Dunn and Dunn themselves, undertaken at the St. John's University Center for the Study of Learning and Teaching Styles, run by Dunn and Dunn. At the time of writing (August 2020), the 2005 meta-analysis has been cited 292 times according to Google Scholar, whereas the rebuttal has been cited 38 times. A similar pattern played out a decade earlier, when an earlier meta-analysis by R Dunn, claiming to validate the Dunn and Dunn Learning Styles model, was published in 1995 (Dunn et al., 1995). This meta-analysis has been cited 610 times, whereas a rebuttal in 1998 (Kavale et al., 1998), has been cited 60 times.

An early attempt by Dunn and Dunn to promote the use of their Learning Styles classification was made on the basis that teachers would be less likely to be the subject of malpractice lawsuits if they could demonstrate that they had made every effort to identify the learning styles of their students (Dunn et al., 1977). This is perhaps an extreme example, but reflective of a general sense that, by identifying a supposed learning style, educators may feel they are doing something useful to help their students.

A particular issue to consider from a pragmatic perspective is that of study quality. Many of the studies did not include key indicators of the quality of survey responses (Kelley et al., 2003; Bennett et al., 2011). For example, none of the studies use a defined, representative sample, and very few include sufficient information to allow the calculation of a response rate. From a traditional research perspective, the absence of these indicators undermines confidence in the generalizability of the findings reported here. Pragmatic research defines itself as identifying *useful* answers to research questions (Newton et al., accepted). From this perspective then, we considered it *useful* to still proceed with an analysis of these studies, and consider the findings holistically. It is useful for the research community to be aware of the limitations of these studies, and we report on these measures of study quality in **Appendix 1**. We also think it is useful to report on the evidence, within our findings, of a lack of clarity regarding what is actually meant by the term "Learning Styles." Taken all together these analyses could prompt further research, using a large representative sample with a high response rate, using a neutral invitation, with a clear explanation of the difference between Learning Styles and styles of Learning. Perhaps most importantly this research should focus on whether educators act on their belief, as described above.

Some of these limitations, in particular those regarding representative sampling, are tempered by the number of studies and a consistency in the findings between studies, and the overall very high rates of self-reported belief in Learning Styles. Thirty-four samples report on this question, and in all studies, the majority of participants agree with the key question. In 25 of the 34 samples, the rate of agreement is over 80%. Even if some samples were not representative, it would seem unlikely to affect the qualitative account of the main finding (although this may be undermined by the other limitations described above).

A summary conclusion from our findings then is that belief in matching instruction to Learning Styles is high and has not declined, even though there is currently no evidence to support such an approach. There are a number of methodological issues which might affect that conclusion, but when taken all together these are insufficient to completely alleviate the concerns which arise from the conclusion; a substantial majority of educators state belief in a technique for which the lack of evidence was established in 2004. In the final section of the discussion here we then consider, from a pragmatic perspective, what are the useful things that we might do with these findings, and consider what could be done to address the concerns which arise from them.

Our findings present some limited evidence that training has some effect on belief in matching instruction to Learning Styles. Only four studies looked at training, but in those studies the percentage who reported that belief in the efficacy of matching instruction to individual Learning Styles dropped from 78.4 to 37.1%. It seems reasonable to conclude that there is a risk of social desirability bias in these studies; if participants have been given training which explains the lack of evidence to support Learning Styles, then they might be reasonably expected to disagree with a statement which supports matching. Even then, for 37.1% of participants to still report that they believe this approach is effective is potentially concerning; it still represents a substantial number of educators. Perhaps more importantly these findings are, like many others discussed here, a self-report of a belief, rather than a measure of actual behavior.

There is already a substantial body of literature which identifies Learning Styles as a neuromyth, or an "urban legend." A 2018 study analyzed the discourse used in a sample of this literature and concluded that the language used reflected a power imbalance wherein "experts" told practitioners what was true or not. A conclusion was that this language may not be helpful if we truly want to address this widespread belief in a method that is ineffective (Smets and Struyven, 2018). We have previously proposed that a "debunking" approach is unlikely to be effective (Newton and Miah, 2017). It takes time and effort to identify student learning styles, and much more effort to then try and design instruction to match those styles. The sorts of instructors who go to that sort of effort are likely to be motivated by a desire to help their students, and so to be told that they have been propagating a "myth" seems unlikely to be news that it is well received.

Considering these limitations from a pragmatic perspective, it does not seem that training, or debunking, is a useful approach to addressing widespread belief in Learning Styles. It is also difficult to determine whether training has been effective when we have limited data regarding the actual use of Learning Styles theory. It may be better to focus on the promotion of techniques that are demonstrably effective, such as retrieval practice and other simple techniques as described in the introduction. There is evidence that these are currently lacking from teacher training (National Council on Teacher Quality, 2016). Many evidence-based techniques are simple to implement, for example the use of practice tests, the spacing of instruction, and the use of worked examples (Young et al., 2014; Weinstein et al., 2018). Concerns exist about the generalizability of education research findings to specific contexts, but these concerns might be addressed by the use of a pragmatic approach (Newton et al., accepted).

In summary then, we find a substantial majority of educators, almost 90%, from samples all over the world in all types of education, report that they believe in the efficacy of a teaching technique that is demonstrably not effective and potentially harmful. There is no sign that this is declining, despite many years of work, in the academic literature and popular press, highlighting this lack of evidence. To understand this fully, future work should focus on the objective behavior of educators. How many of us actually match instruction to the individual Learning Styles of students, and what are the consequences when we do? Does it matter? Should we instead focus on promoting effective approaches rather than debunking myths?

DATA AVAILABILITY STATEMENT

The original contributions presented in the study are included in the article/**Supplementary Material**, further inquiries can be directed to the corresponding author/s.

AUTHOR CONTRIBUTIONS

PN conceived and designed the study, undertook searches, extracted data, undertook analysis, drafted manuscript, and finalized manuscript. AS re-extracted data and provided critical comments on the manuscript. AS and PN undertook PRIMSA quality analyses.

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SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/feduc.2020.602451/full#supplementary-material

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Predicting Student Performance Using Machine Learning in fNIRS Data

Amanda Yumi Ambriola Oku and João Ricardo Sato*

Center of Mathematics, Computing and Cognition, Universidade Federal Do ABC, São Bernardo Do Campo, Brazil

Increasing student involvement in classes has always been a challenge for teachers and school managers. In online learning, some interactivity mechanisms like quizzes are increasingly used to engage students during classes and tasks. However, there is a high demand for tools that evaluate the efficiency of these mechanisms. In order to distinguish between high and low levels of engagement in tasks, it is possible to monitor brain activity through functional near-infrared spectroscopy (fNIRS). The main advantages of this technique are portability, low cost, and a comfortable way for students to concentrate and perform their tasks. This setup provides more natural conditions for the experiments if compared to the other acquisition tools. In this study, we investigated levels of task involvement through the identification of correct and wrong answers of typical quizzes used in virtual environments. We collected data from the prefrontal cortex region (PFC) of 18 students while watching a video lecture. This data was modeled with supervised learning algorithms. We used random forests and penalized logistic regression to classify correct answers as a function of oxyhemoglobin and deoxyhemoglobin concentration. These models identify which regions best predict student performance. The random forest and penalized logistic regression (GLMNET with LASSO) obtained, respectively, 0.67 and 0.65 area of the ROC curve. Both models indicate that channels F4-F6 and AF3-AFz are the most relevant for the prediction. The statistical significance of these models was confirmed through cross-validation (leave-one-subject-out) and a permutation test. This methodology can be useful to better understand the teaching and learning processes in a video lecture and also provide improvements in the methodologies used in order to better adapt the presentation content.

Keywords: neuroscience, fNIRS, education, prefrontal cortex, machine learning, logistic regression, random forest

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****Correspondence:***
Amanda Yumi Ambriola Oku
amanda.yumi@ufabc.edu.br

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1. INTRODUCTION

The interactivity in a virtual teaching environment can increase student engagement and, therefore, reinforces learned concepts and provide on-demand learning capacity (Jonassen et al., 1995). Empirical assessments have emerged in recent research, such as studies by Wachtler et al. (2018), which show that video lectures with quizzes can be used to increase knowledge, intensify engagement, and raise attention.

Although it is possible to measure student performance through the results of quizzes in class, a relevant factor to be studied is the involvement of students in the execution of tasks through the mapping of brain states during the task. Usually, cognitive neuroscience experiments study psychological processes through controlled manipulations, reducing the behavior of one of its components. However, this framework is not suitable when one wishes to generalize the characteristics of new situations from full descriptions of the behavior (Varoquaux and Poldrack, 2018). For instance, Barreto et al. (2020)and Noah et al. (2015) indicate the importance that studies involving music an dance be carried out under natural conditions. Similarly, Lamb et al. (2018) performs experiments under naturalistic conditions for the evaluation of science education.

We address this issue by performing an experiment in a more realistic setting. Specifically, we collected brain data with a fNIRS (functional near-infrared spectroscopy) device from students while they were watching a video lecture and answering questions. The fNIRS device was chosen due to its acquisition systems that collect data of hemodynamic states in several brain regions in a naturalistic, comfortable, and safe manner for participants (Noah et al., 2015). Safe levels of light (with wavelengths between 650 and 1,000 nm) were used to infer the variation in the level of oxygenation of brain tissue in a non-invasive way, which penetrates the biological tissue and reaches the cortex, allowing the analysis of oxygenation. hemoglobin (HbO_2), deoxyhemoglobin (HHb) and total hemoglobin (tHb; tHb = (HbO_2) + HHb) from cerebral blood (Delpy and Cope, 1997). The fNIRS technical limitations include superficial depth cortical evaluation (Ferrari et al., 2004). Specifically, we collected fNIRS data from the Prefrontal cortex (PFC).

The PFC has a central role in cognitive control. It has interconnections with brain areas that process external information (with all the sensory systems and structures of the cortical and subcortical motor system) and with internal information (limbic and midbrain structures involved in affection, memory, and reward). It has access and the means to influence processing in all major forebrain systems and can provide a means of synthesizing the various sources of information related to a given objective (Miller et al., 2002). McGuire and Botvinick (2010) shows there are indications that prefrontal cortex neurons appear to have a crucial ability for cognitive control, transmitting knowledge about a specific goal-directed task. Furthermore, Lamb et al. (2018) shows that fNIRS imaging of the prefrontal cortex can be useful to educators, since this region is responsible for problem solving, memory, and social behavior. However, this study also shows that tasks involving large amounts of unstructured processing, such as video lectures, can be challenging, since they generate less dynamic response within the prefrontal cortex than structured tasks.

In this paper, the fNIRS data from the PFC was used to create predictors for a student's answers. These predictors were obtained by applying machine learning algorithms to the data. In particular, we used random forests and penalized logistic regression algorithms. These algorithms allow one to understand the structure of existing data and generate prediction rules for new observations.

2. MATERIALS AND METHODS

2.1. Participants

A total of 21 participants were recruited for participation but 3 of them were excluded (one for low signal quality and two for not meeting the health requirements). All 18 participants (10 female, 8 male) were right-handed, had normal vision and hearing, and mean age 25.6 ± 4.6 (range 18–40 years). No subject had an history of neurological or psychiatric disorders. Participants were recruited among undergraduate and graduate students in fields of Science. All participants alleged to have little or no prior knowledge in Astronomy. Signed consent was obtained from all members prior to participation. The Federal University of ABC - Ethics Committee approved the experiment. The experiment was performed in accordance with all local relevant guidelines and regulations. All subjects participated voluntarily and without any financial compensation, as required by federal laws.

2.2. Experiment

The experiment's tasks consisted of watching the first class in an Astronomy course while answering several multiple choice questions. The class was entitled "Astronomy: A general introduction", and was chosen from a publicly available e-learning course from the Virtual University of São Paulo State (UNIVESP). The video's content usually does not belong to the basic education curriculum and requires reasoning and attention for understanding calculations and order of events. It was chosen since it brings new content to most students and does not require a large amount of previous knowledge.

Before running the main experiment, we tested the hypothesis that answering correctly depended on watching the video. This hypothesis was tested by applying the a quiz with multiple choice questions to a control group with 116 participants who did not watch the video lecture. The probability of a correct answer without watching the video was found based on a binomial test. The test did not reject the hypothesis that, without answering the video, participants answer correctly no better than by chance.

The main experiment was performed using Edpuzzle (http://edpuzzle.com/), an American platform for online learning. This platform was validated by Abou Afach et al. (2018) and is used by colleges, open courses, and universities. It was also validated in Brazil by researchers in education, which signaled it could be used successfully by local students (Lombardi and Gitahy, 2017).

We collected data of functional near-infrared spectroscopy (fNIRS) placed over the PFC (responsible for planning complex cognitive behavior, decision making, and moderating social behavior) of 18 undergraduate and graduate students using NIRSport equipment (company NIRx Medical Technologies). In the experiment, subjects were seated in a comfortable chair in a quiet and ventilated room.

The subjects were asked to relax and to remain still during the experiment. They watched a free recorded lecture (27 min) with 10 multiple-choice exercises (**Figure 1**). As in real classroom situations, there was no indication of the times that they would be asked future questions.

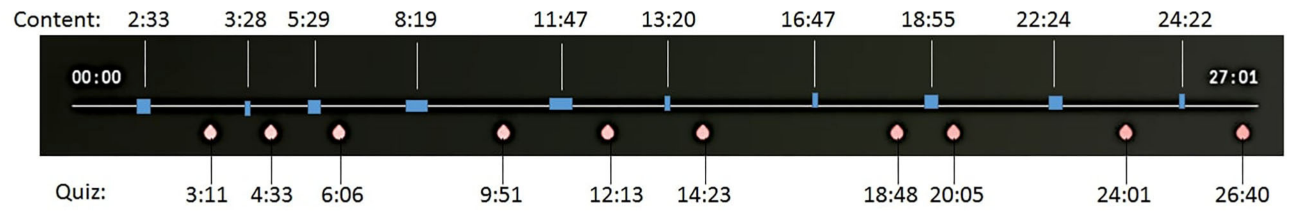

FIGURE 1 | The questions are based on content exposed at earlier times throughout the video (indicated in blue). The red dots show the exact timing of the questions.

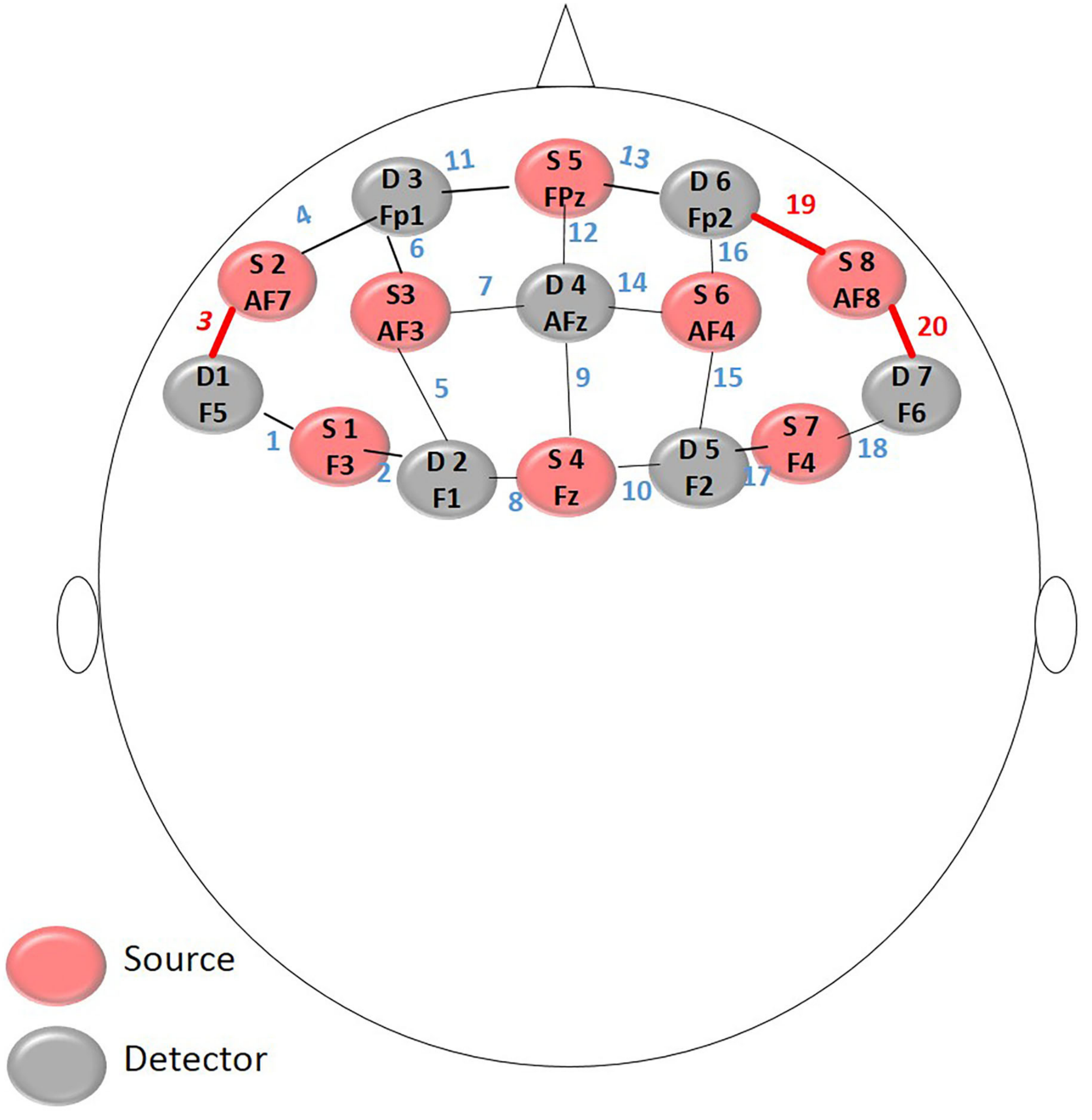

FIGURE 2 | Montage layout: The position of the optodes follows the universal configuration of the 10-10.

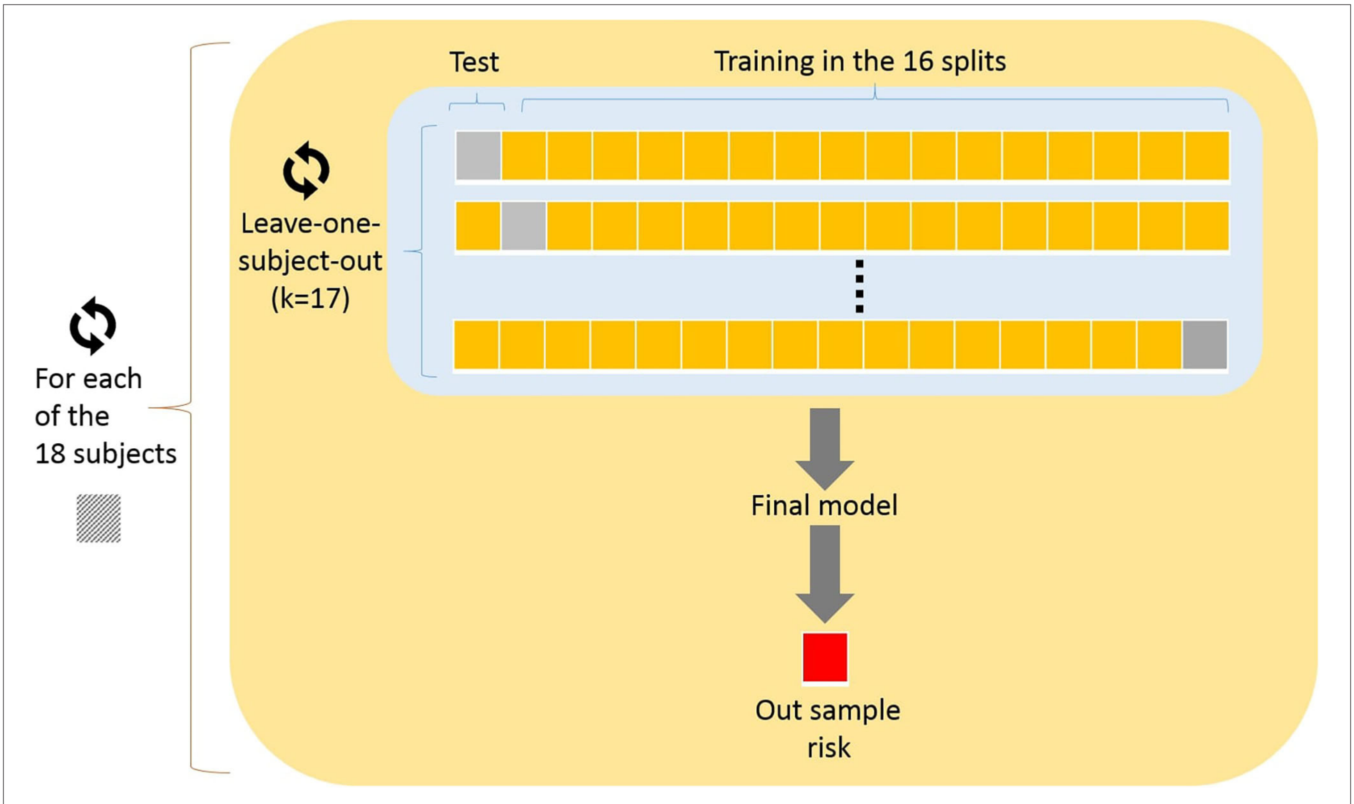

FIGURE 3 | Double cross-validation implemented: In the outer (external) loop of double cross-validation, each interaction excludes one subject and all remaining data subjects are divided into two subsets referred to as training and test sets. The training set used in the inner (internal) loop, while the test set was exclusively used for model assessment.

2.3. Data Acquisition

The position of the optodes follows the universal configuration of the 10-10 electroencephalogram (EEG) system (Koessler et al., 2009). The 8 emitters and 7 detectors are positioned in the form: Sources in F3, AF7, AF3, Fz, Fpz, AF4, AF8, F4 and the Detectors in F5, F1, Fp1, AFz, F2, Fp2, F6 under an approximate distance of 3 cm between the optodes and resulting in the collection of oxyhemoglobin and deoxyhemoglobin from 20 channels, as **Figure 2**.

The recording of the PFC region was conducted on a multi-channel continuous wave system using NIRSport equipment (company NIRx Medical Technologies). This system consists of 8 illumination sources and 8 detection sensors with two wavelengths of 760–850 nm. The sampling rate of NIRSport is 62.5 Hz, as the device implements time multiplexing, which means that only one LED is turned on at each time, the sampling rate for each data channel is 7.81 Hz. The data were recorded by a computer during the measurements using NIRStar software (NIRx Medizintechnik GmbH, Berlin, Germany)

2.4. Data Preprocessing

Raw data from the NIRStar were processed using the NIRSLab-2014 (NIRx Medizintechnik GmbH,Berlin, Germany) via the Matlab 2007b (Mathworks, Natick, MA, USA) (Xu et al., 2014) software using a 0.01–0.2 Hz bandpass filter to reduce physiological signal artifacts at the cutoff frequencies of the global deviations ($<$ 0.01 Hz), systemic interferences such as respiration rate ($>$ 0.2Hz) and cardiac cycles ($>$ 0.5Hz). We used the modified Beer-Lambert law (Mesquita and Covolan, 2008), to find the variations in oxygenated hemoglobin (HbO_2) and deoxygenated hemoglobin (HHb) cited by Delpy and Cope (1997). We removed some motion artifacts manually (spikes) where HbO2 and HHb increased or decreased in unison based on visual inspection of the record (Lloyd-Fox et al., 2010). Afterward, we used the mean of the entire timeline as a baseline

TABLE 1 | Confusion matrix—random forest.

Predicted \Actual	Incorrect	Correct
Incorrect	34	44
Correct	18	84

TABLE 2 | Confusion matrix—GLMNET.

Predicted \Actual	Incorrect	Correct
Incorrect	32	46
Correct	20	82

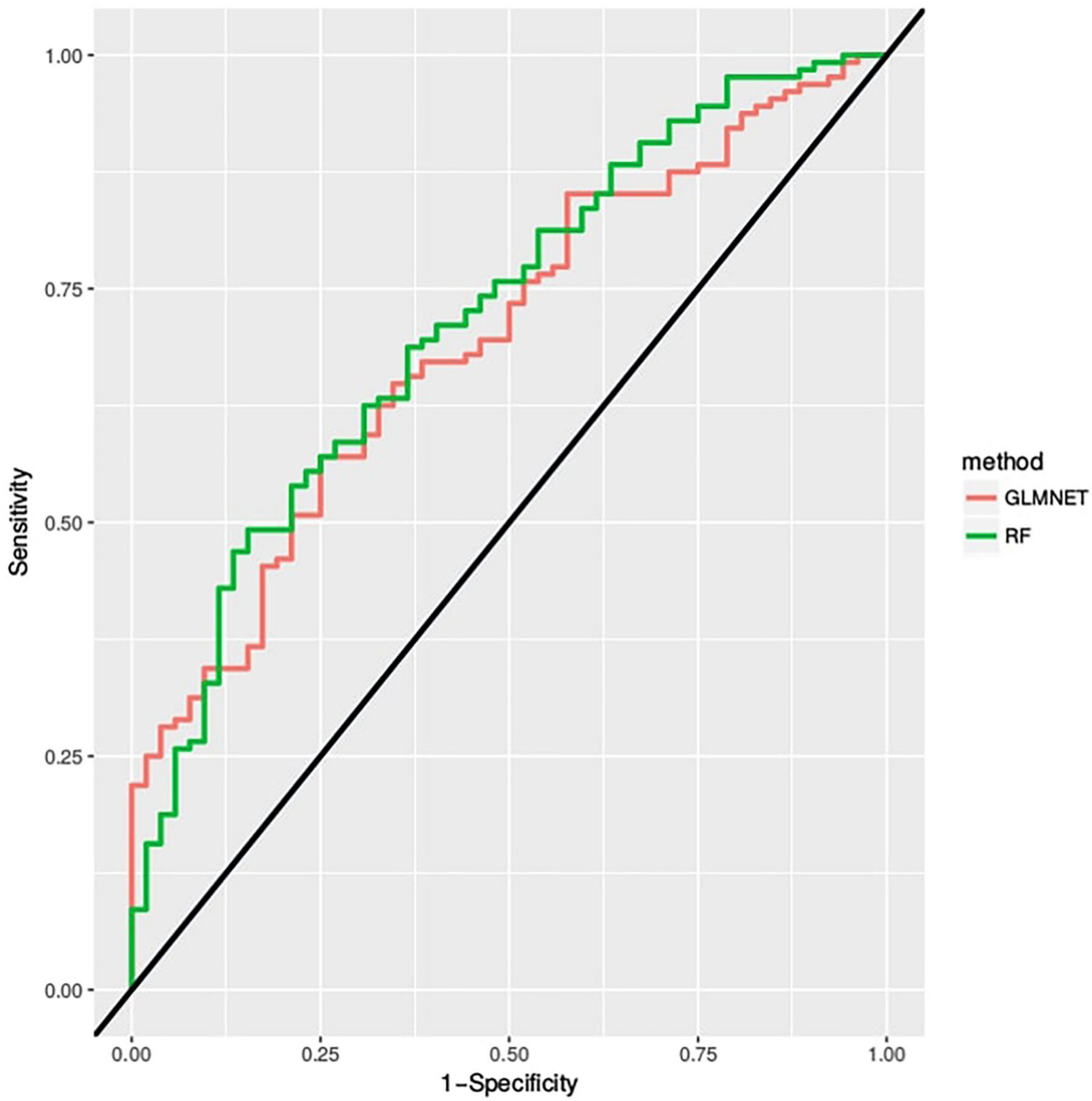

FIGURE 4 | The ROC curve is created by plotting the true positive rate (sensitivity) against the false positive rate (specificity) at various threshold settings.

and differential path length factor (DPF) of 7.25 for the 760 nm and 6 wave, 38 for 850 nm lengths.

After computing the states of oxyhemoglobin (HbO_2) and deoxyhemoglobin (HHb), the signal was averaged and grouped according to 10 exercises and 18 students, totaling 180 observations over 20 channels. The signal's standard deviation was also computed in each of these groups. However, since this feature did not improve the statistical analysis, it was not used in the final model.

2.5. Statistical Analysis

All learning algorithms were implemented in the R language (4.0.3 version). The "magrittr" and "tidyverse" packages were used in building the final database. The packages "randomForest" and "GLMNET" were used for fitting the Random Forest and Penalized Logistic Regression classifiers. Also, the "ROCR" package was used for performance analysis.

Logistic regression performs binary classification (dichotomous output labels), returning the probability that the object belongs to each class. In this way, the cost function can be the difference between the predicted probability and label 0 or 1. This cost can be estimated by calculating the average loss over all objects in a test set, similarly as done in linear regression.

Simple logistic regression can cause overfitting when dealing with many covariates. To mitigate this problem, we applied LASSO (least absolute shrinkage and selection operator) to our data. This is a regularization method that penalizes large parameter values and usually yields solutions in which the

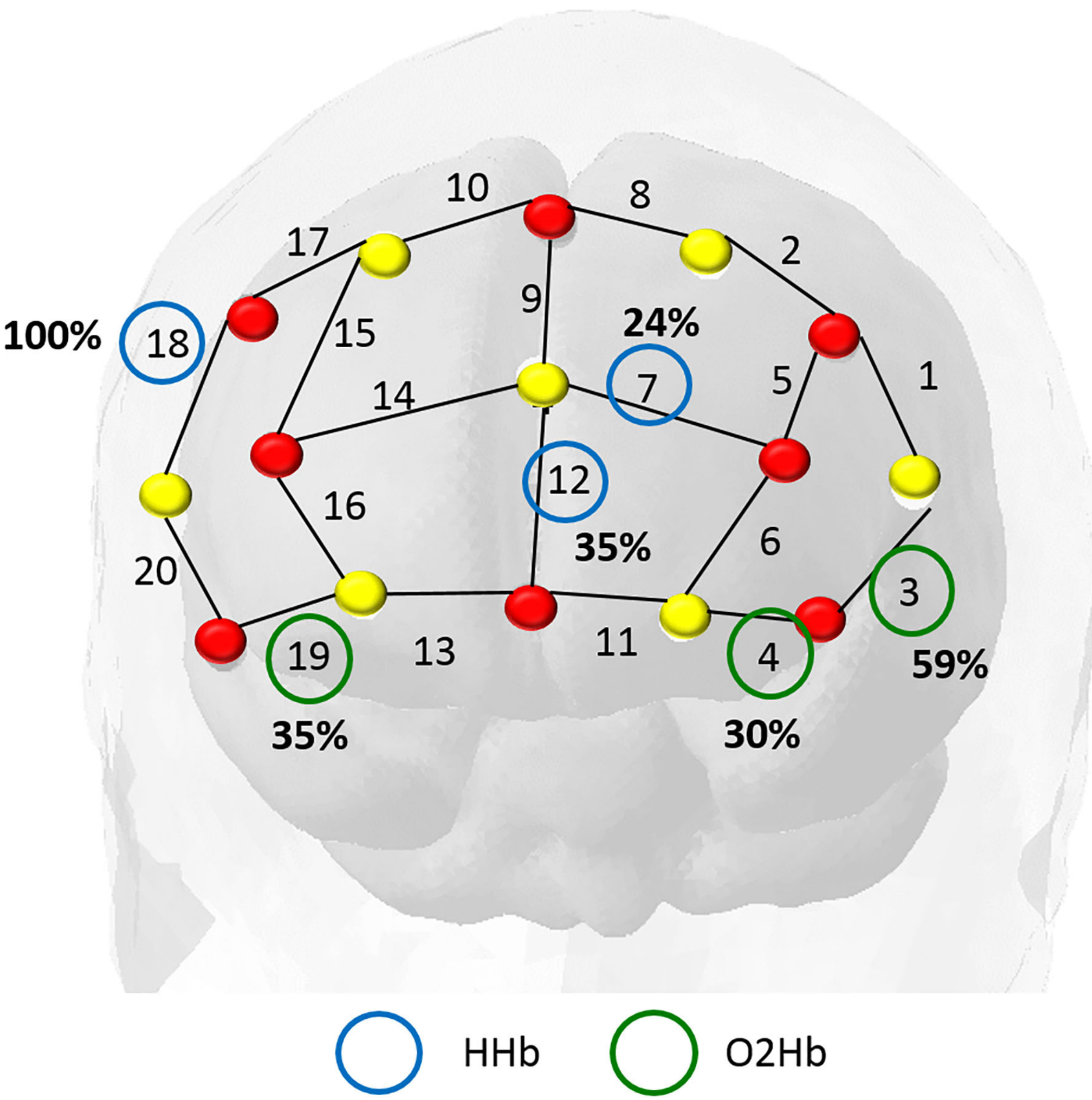

FIGURE 5 | In this map, the red dots represent the sources and the yellow dots the detectors. We identified the most important channels from the total iterations in training the model. The frequency of the main covariables identified were: deoxyhemoglobin (blue circles) in channel 18 (highly relevant in all subjects) and oxyhemoglobin (green circles) in channel 3 (present in 60% of the subjects).

estimates of several of the parameters are zero (sparse solutions). This method is done by maximizing the log-likelihood added by a penalty factor. More details about LASSO can be found in section A.1 of the **Appendix**.

2.6. Cross Validation

Both our algorithms (Random Forest and GLMNET with LASSO) involved training 180-response BD (10 video ranges for each of the 18 subjects). Each of these has 40 covariates for prediction [mean (HbO_2) and mean (HHb) for each of the 20 channels obtained in each video snippet].

Using a small database to learn the parameters of a prediction function and testing it on the same data can find a perfect score but would fail to predict yet-unseen data. This situation is called overfitting and can be overcome by cross-validation.

The performance of Random Forest and LASSO logistic regression was evaluated using different types of cross-validation. The Random Forest was evaluated using simple leave-one-subject-out cross-validation. Also, we assessed the performance of LASSO logistic regression using double cross-validation (leave-one-subject-out) as illustrated in **Figure 3**. The double cross-validation process implemented comprises two nested cross-validation loops which are referred to as internal and external cross-validation loops. In the outer (external) loop of double cross-validation, each interaction excludes one subject and all remaining data subjects are divided into two subsets

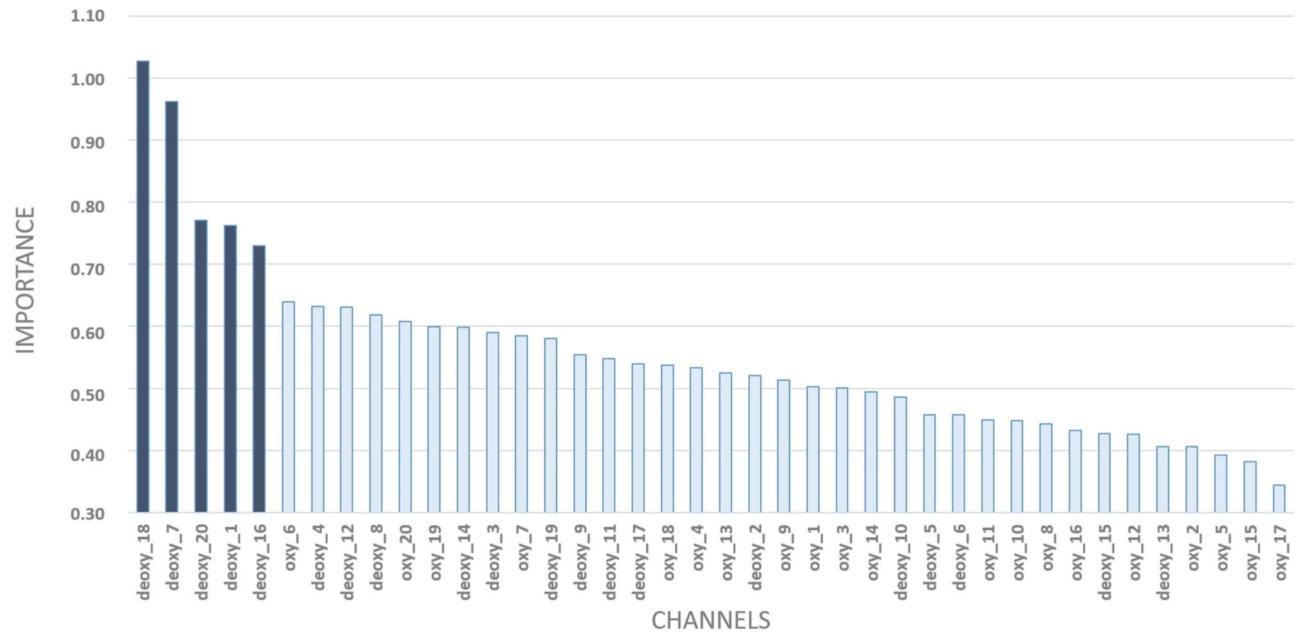

FIGURE 6 | Random forest outputs: level of importance of each covariate with a detailed zoom at the top-5 ones.

referred to as training and test sets. The training set used in the inner (internal) loop of double cross-validation for model building and model selection, while the test set was exclusively used for model assessment.

3. RESULTS

The Random Forest and the GLMNET obtained satisfactory results with, respectively, areas of 0.67 and 0.65 under the ROC curve in **Figure 4**. Also, We represented through the confusion matrix of both algorithms (**Tables 1**, **2**) the instances of the predicted classes: Each row represents the instances of the predicted model while the column represents the real results of the students' performance. Both models obtained a good fit on identifying actual right answers (correct/correct) and wrong answers (incorrect/incorrect). The GLMNET LASSO had an accuracy of 0.63 ± 0.036, a sensitivity of 0.62 ± 0.067, a specificity of 0.64 ± 0.042, and a Cohen's kappa coefficient of 0.22 (fair on the Kappa scale). The random forest had a slightly better result, with an accuracy of 0.66 ± 0.035, a sensitivity of 0.63 ± 0.066, a specificity of 0.66 ± 0.042, and a Cohen's kappa coefficient of 0.26 (fair on the Kappa scale).

We also showed that the models are in fact better than chance through a permutation test, which evaluates whether the model is uninformative. This test can be easily applied to a wide range of statistical learning methods, including some in which a measure of variability is difficult to obtain and is not automatically produced by the statistical software (Friedman et al., 2001).

We repeated the same procedure of adjusting the models with the shuffled response variables and calculated the AUC (area under the ROC curve) for each one of the 1,000 iterations.The total number of cases that resulted in a better model than the original was 3 cases for the Random Forest, thus obtaining a *p*-value of 0.003 (thus rejecting the null hypothesis) and the total number of cases that resulted in a better model than the original was 1 in GLMNET, thus obtaining a p-value of 0.001 (also rejecting the null hypothesis).

The output of the models identified which channels resulted in better predictors for the exercises.

3.1. Main Predictors—Penalized Logistic Regression

For the GLMNET model, we calculated the frequency of the selected channels in each iteration of the outer loop of the cross-validation, as displayed in **Figure 5**. We verified that the covariates (HHb) in channel 18 (referring to regions F4-F6 in the 10-10 system) and the (HbO_2) in channel 3 (F5-AF7) had greater weight in the prediction, being used in, respectively, 100 and 59% of the subjects.

The relevant channels according to this model are the areas of channel 4 (AF7- F5), and channel 18, regions F4-F6, both corresponding to middle frontal cortex (Koessler et al., 2009; Balconi and Fronda, 2020). The region belongs to the dorsolateral prefrontal cortex (Bandeira et al., 2019) which is associated with the cognitive process, working memory, cognitive flexibility, planning, inhibition, and abstract reasoning (Zgaljardic et al., 2010).

As for the most important channels for each of the models, it is worth mentioning that the penalty of the channels in the GLMNET with LASSO does not imply that they are not

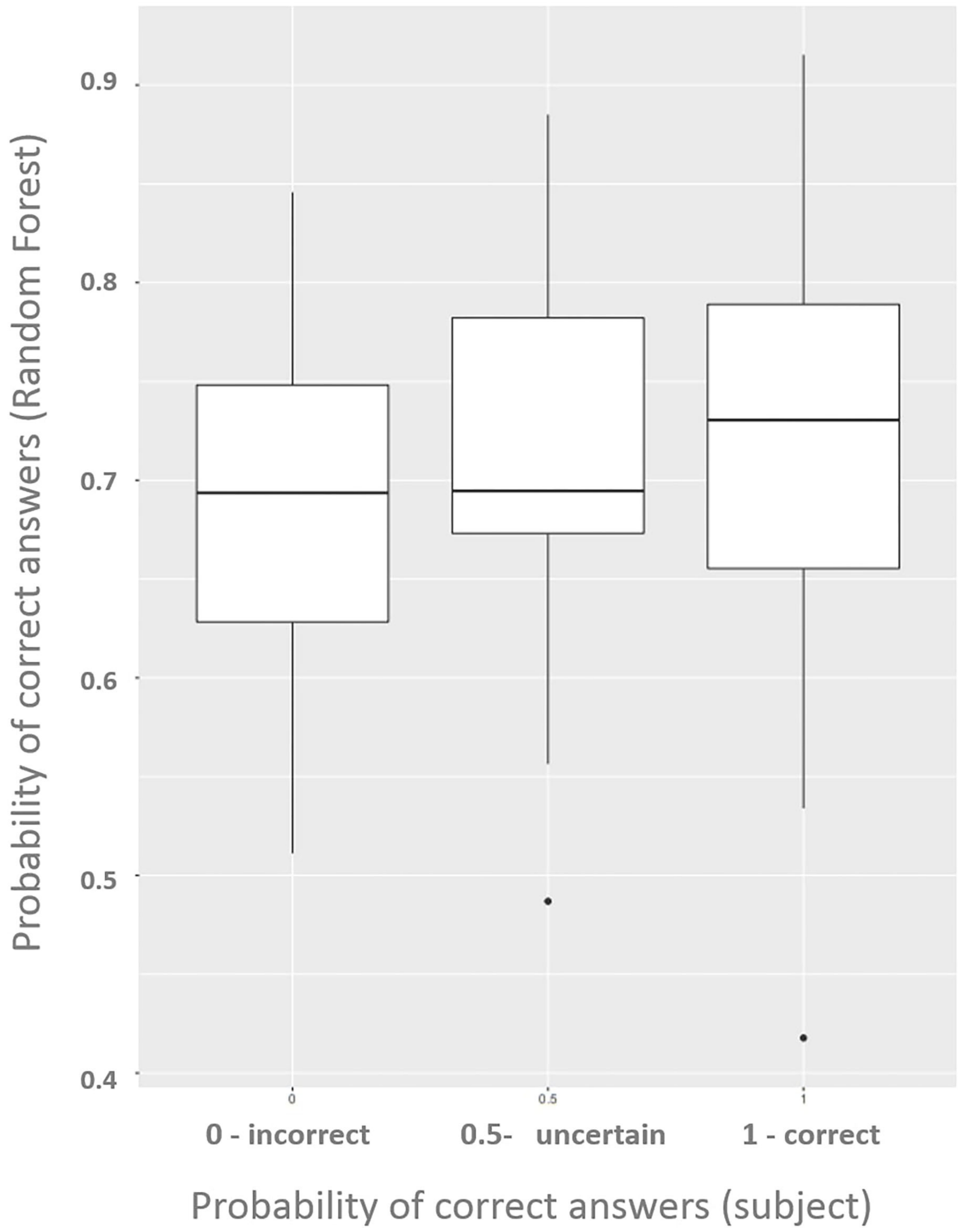

FIGURE 7 | Boxplots show differences between the groups: 1, certainly right exercise; 0.5, not sure/next idea; 0, probably wrong/random guess.

explanatory for the response variable, but rather, there may be a correlation with another channel that is explanatory and therefore suffered a penalty.

3.2. Main Predictors—Random Forest

The Random Forest Model indicated high predictive power from the covariates (HHb) in channel 18 (**Figure 6**). Besides this

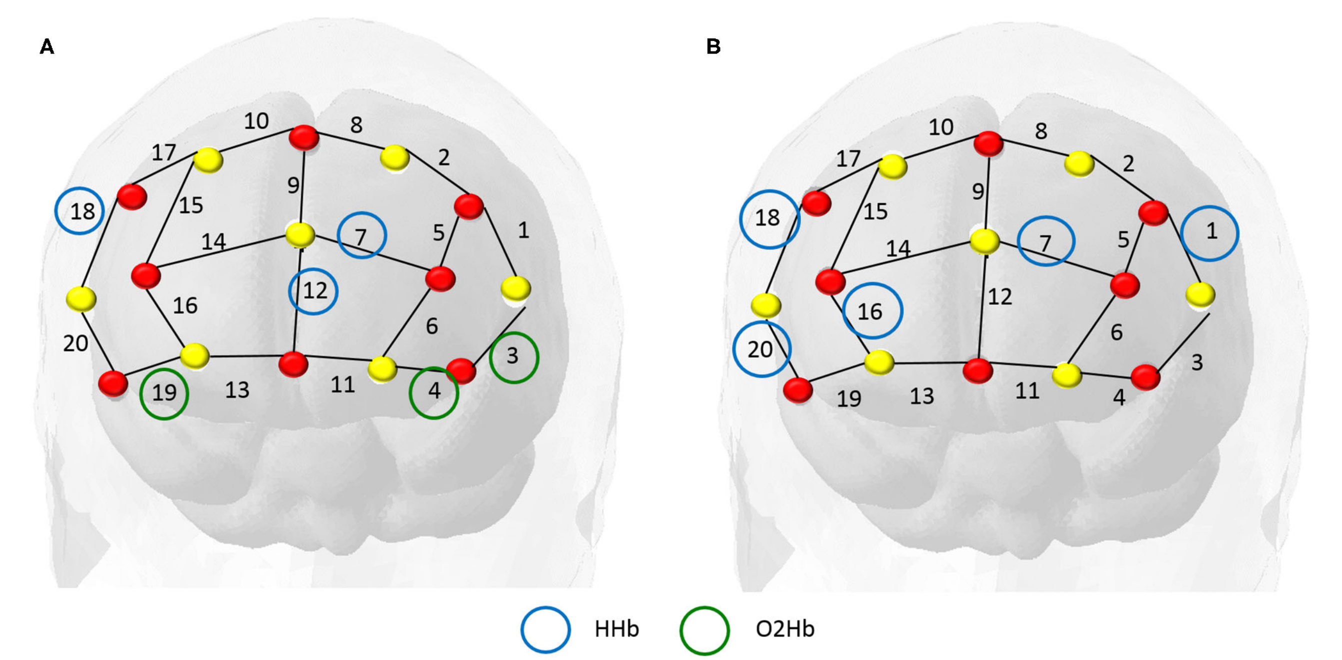

FIGURE 8 | In these maps, the red dots represent the sources and the yellow dots the detectors. Panel **(A)** refers to the GLMNET Model output and strongly indicates channel 18 HHb (F4-F6) and channel 4 O2Hb (AF7-FP1). Panel **(B)** refers to the Random Forest Model output and indicates greater relevance for channel 18 HHb (F4-F6) and channel 7 HHb (AF3- AFz). The channel 18 region is the dorsolateral prefrontal region, associated with attention and working memory.

channel, the following were the most relevant: 7 (AF3-AFz), 20 (AF8-F6), 1 (F3 and F5), and 16 (AF4 and Fp2). In addition to working memory, they also show semantic aspects of language.

3.3. Hits Expectations vs. Prediction

In addition to identifying which channels are more explanatory for identifying the errors in the questions per individual, it was also possible to evaluate the levels of student involvement in interactive classes. We analyzed which types of questions are more difficult to answer by comparing the error rate with moments when the students declared to have lost concentration.

We compared the results of the random forest prediction with what the volunteers believed they had got right and mentioned at the end of the experiment. The **Figure 7** shows how the model differentiates hits and errors using only signals of oxyhemoglobin and deoxyhemoglobin in each question.

The Random Forest model indicates a slightly higher probability of correct answers among the cases in which the subjects believe they have hit the exercise. Also, it indicates a low probability of correct answers for the cases in which the subjects declared to have felt indecisive or believed to have mistaken the question (in this case, with low differentiation between them).

For the training of the models, it was necessary to identify the hemodynamic signs linked to the questions. We conducted tests to assure that the questions alone were not enough to predict student successes and errors (which would show an error in the design of the experiment).

The analyzed regions of the experiment are only suitable for exercises with the fixation of theoretical content. Mathematical reasoning, calculation, and perception have not been validated.

4. DISCUSSION

In this research, we fit a predictive model for a students' correctness of answers in an interactive class based on PFC activity. These models allowed the identification of which regions are most relevant and influence results the most.

Both models (**Figure 8**) indicated that the information from channels F4-F6 (based on the EEG 10-10 system) had the greatest impact on the predictive model (**Figure 4**), suggesting a significant contribution to language understanding and semantic decision tasks.

Our models are consistent with other articles in the literature. For instance, (Liu and Ayaz, 2018) shows that perceived speech can be identified from the listeners' brain signals measured with fNIRS and (Herff et al., 2014) shows that measuring hemodynamic responses in the PFC with fNIRS, they showed the degree of workload a subject was experiencing, instead of only identify if there was an engagement during the tasks. Furthermore, MacDonald et al. (2000) and Dosenbach et al. (2006) use fNIRS data to show that brain activity can distinguish between high and low levels of task engagement. Specifically, they detected differences in the brain activity in the dorsolateral prefrontal cortex (*dorsolateral prefrontal cortex*—DLPFC) while participants alternated between performing and not performing a cognitive task.

With error rates in the models below 30%, our work can be suggested to assess levels of student involvement in tasks to validate new teaching content through videos, allowing us to evaluate whether students can assimilate content from fNIRS signals.

Despite the results obtained, the study has some limitations. For instance, the model considers the NIRS signal related to a single video lesson. Further studies are needed to have more information about students' behavior and performance during the task. Also, in the collection of fNIRS data in this experiment, we did not use short distance detectors, which could assist in the exclusion of extracerebral signals around the sources (Tachtsidis and Scholkmann, 2016).

An unexpected result was the high importance of HHb in both predictive models. Usually fNIRS studies indicate a high influence of $HHbO_2$ on results, with higher signal-to-noise ratio SNR than HHb. Fishburn et al. (2014) shows the fNIRS sensitivity to detect linear changes in activation and functional connectivity in response to cognitive load, using $HHbO_2$ and HHb had low correspondence. Also, Fishburn et al. (2014), Leon-Dominguez et al. (2014), and Barreto et al. (2020) show significant results for HHb. The sensitivity and SNR are core parameters during the fNIRS measurement and from the results obtained, further investigation is needed regarding the importance of HHb data in the models and new systematic analysis of SNR.

Since our primary goal was limited to investigating the PFC, we did not acquire signals from other brain regions. Although this assembly of optodes provides favorable conditions for more realistic situations, complementary studies with Functional Magnetic Resonance Imaging (fMRI) could perform to accurately identify other brain regions and also identify a precise location of Brodmann's areas involved during the task.

This study opens perspectives for a better understanding of the PFC during the execution of tasks and experiments in real situations. For further studies, we understand that it is important to continue assessing the level of sustained attention of students from hemodynamic states through models for classifying the involvement in the task rather than subtasking specific tasks.

DATA AVAILABILITY STATEMENT

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

ETHICS STATEMENT

The studies involving human participants were reviewed and approved by Federal University of ABC - Ethics Committee approved all this experiment. The experiment was performed in accordance with all local relevant guidelines and regulations. The patients/participants provided their written informed consent to participate in this study.

AUTHOR CONTRIBUTIONS

AO and JS: designed the study, collected, and analyzed the data and revised the manuscript. All authors have read and agreed to the published version of the manuscript.

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Conflict of Interest: The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

A. APPENDIX

A.1. LASSO

Logistic regression is a supervised learning method that is used for binary response variables. Let $Y_i \in \{0,1\}$ be a response variable and $\mathbb{X}_i$ be a vector of covariates. In logistic regression, the logit of $\mathbb{P}(Y_i = 1|\mathbb{X}_i)$ follows a linear equation, that is,

$$\log\left(\frac{\mathbb{P}_\beta(Y_i = 1|\mathbb{X}_i)}{1-\mathbb{P}_\beta(Y_i = 1|\mathbb{X}_i)}\right) = \beta^t\mathbb{X}_i \quad \text{, where } \beta \text{ are unknown coefficients.} \tag{A1}$$

Using Equation (A1), it is possible to compute the log-likelihood of coefficients, $l(\beta)$, for the observed sample.

$$l(\beta_0) = \sum_{i=1}^{n} \log(\mathbb{P}_{\beta_0}(Y_i = y_i|\mathbb{X}_i)) \tag{A2}$$

The value of $l(\beta_0)$ is a measure of how likely it is that $\beta = \beta_0$. Based on this interpretation, a common choice of estimator for β is the one which maximizes $l(\beta_0)$, the maximum likelihood estimator. However, this estimator can lead to overfitting when the sample size is small relatively to the number of covariates. In this case, it is common to use regularized maximum likelihood estimators.

LASSO is one alternative for performing regularized logistic regression. In this framework, one estimates β by maximizing

$$s(\beta_0) = l(\beta_0) - \lambda\sum_{i=1}^{d}|\beta_i|. \tag{A3}$$

Equation A3 leads to a trade-off between how likely is β and how small are its values. This trade-off often avoids overfitting and leads to better estimators. Furthermore, in LASSO one uses a l_1 penalty, $\sum_{i=1}^{d}|\beta_i|$. This penalty often leads to estimates for β that have many zeroes. That is, LASSO estimation often automatically performs feature selection.

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BRIEF RESEARCH REPORT
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A New Statistical Approach for fNIRS Hyperscanning to Predict Brain Activity of Preschoolers' Using Teacher's

Candida Barreto[1], Guilherme de Albuquerque Bruneri[2], Guilherme Brockington[3], Hasan Ayaz[4,5,6,7,8] and Joao Ricardo Sato[1,9]*

[1] Center of Mathematics, Computing and Cognition, Federal University of ABC, Sao Bernardo do Campo, Brazil, [2] Physics Institute, Federal University of São Paulo, São Paulo, Brazil, [3] Center for Natural and Human Sciences, Universidade Federal do ABC, Santo André, Brazil, [4] School of Biomedical Engineering, Science and Health Systems, Drexel University, Philadelphia, PA, United States, [5] Department of Psychology, College of Arts and Sciences, Drexel University, Philadelphia, PA, United States, [6] Drexel Solutions Institute, Drexel University, Philadelphia, PA, United States, [7] Department of Family and Community Health, University of Pennsylvania, Philadelphia, PA, United States, [8] Center for Injury Research and Prevention, Children's Hospital of Philadelphia, Philadelphia, PA, United States, [9] Interdisciplinary Unit for Applied Neuroscience, Federal University of ABC, Sao Bernardo do Campo, Brazil

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Mingming Zhang,
Shanghai Normal University, China

****Correspondence:***
Candida Barreto
candida.ferreira@ufabc.edu.br

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Hyperscanning studies using functional Near-Infrared Spectroscopy (fNIRS) have been performed to understand the neural mechanisms underlying human-human interactions. In this study, we propose a novel methodological approach that is developed for fNIRS multi-brain analysis. Our method uses support vector regression (SVR) to predict one brain activity time series using another as the predictor. We applied the proposed methodology to explore the teacher-student interaction, which plays a critical role in the formal learning process. In an illustrative application, we collected fNIRS data of the teacher and preschoolers' dyads performing an interaction task. The teacher explained to the child how to add two numbers in the context of a game. The Prefrontal cortex and temporal-parietal junction of both teacher and student were recorded. A multivariate regression model was built for each channel in each dyad, with the student's signal as the response variable and the teacher's ones as the predictors. We compared the predictions of SVR with the conventional ordinary least square (OLS) predictor. The results predicted by the SVR model were statistically significantly correlated with the actual test data at least one channel-pair for all dyads. Overall, 29/90 channel-pairs across the five dyads (18 channels 5 dyads = 90 channel-pairs) presented significant signal predictions with the SVR approach. The conventional OLS resulted in only 4 out of 90 valid predictions. These results demonstrated that the SVR could be used to perform channel-wise predictions across individuals, and the teachers' cortical activity can be used to predict the student brain hemodynamic response.

Keywords: hyperscanning, fNIRS, teacher-student interaction, support vector regression, machine learning

INTRODUCTION

Hyperscanning is a neuroimaging acquisition concept that consists of simultaneously measuring the brain activities of two or more individuals while interacting to assess the interpersonal neural synchrony (INS) (Mukamel et al., 2005; Hasson et al., 2012; Wang et al., 2018; Balconi et al., 2019). Functional near-infrared spectroscopy (fNIRS) has gained attention in this field, as it is a modern neuroimaging technique with advantages for naturalistic experiments (Balardin et al., 2017; Curtin and Ayaz, 2018). It is less susceptible to movement artifacts than electroencephalography (EEG) and functional magnetic resonance image (fMRI). It allows the investigation of individuals' brains in less constrained movement conditions, such as daily life tasks (Ayaz et al., 2013; Pinti et al., 2018a,b; Barreto et al., 2020). These advantages make fNIRS an attractive neuroimaging modality to investigate the brain and explore some populations, such as children, who usually present more movement and require fewer constraints during the experiments (McDonald and Perdue, 2018). Hyperscanning studies with fNIRS have brought new insights about the adult-child brain synchronization that could not be explored before due to these limitations (Piazza et al., 2020). For instance, studies that demonstrated neural coupling across parent-child in cooperation tasks and research that showed the effects of stress in the parent-child brain synchronization (Reindl et al., 2018; Azhari et al., 2019; Miller et al., 2019). Those studies required an unconstrained environment since the infant/child cannot be entirely quiet to avoid movement artifacts, in the case of EEG, or even they cannot go inside an fMRI device.

Another field that benefited from the synergy of device portability and hyperscanning acquisition to investigate subjects' neural coupling is Education. For many years, the relationship between teacher and student has been investigated only in behavioral studies (Battro et al., 2013). A lack in the literature needs to be fulfilled about the neural correlates related to such a meaningful interaction (Battro, 2010). Recent studies have focused on this matter (Dikker et al., 2017). The first study investigating the teacher-students neural coupling was based on performing a Socratic dialog task (Holper et al., 2013). The authors found a correlation between the student's and teacher's hemodynamic signals only when the transfer of knowledge was successful. Another study investigated the teacher-learner process through an fNIRS hyperscanning of the pre-frontal cortex (PFC) of teachers and students playing a video game (Takeuchi et al., 2017). They showed evidence that the teacher's left PFC might be involved in integrating the teacher's teaching process, and the student's learning state. fNIRS hyperscanning was also applied to record dyads' brain activity while learning-teaching a new song (Pan et al., 2018). In this case, brain synchronization occurs when learners observe the instructor's vocal behavior. Zheng et al. (2018) have demonstrated that teacher-student interaction is a complex process supported by the prediction-transmission hypothesis. According to this, the teacher will predict the state of the student(s) understanding theory before starting any teaching strategy (Kline, 2015). Although this is a theoretical hypothesis that has been considered to explain some aspects of the teaching-learning process, Zheng et al. (2018) introduced the possibility of using the hyperscanning approach to investigate the brain mechanisms that may underlie it. Their research demonstrated neural evidence supporting this hypothesis and indicated that the interbrain synchronization between teacher and student might enhance the teaching results (Zheng et al., 2018; Sun et al., 2020).

The methodological framework used to analyze the data from the fNIRS hyperscanning studies usually relies on classical approaches such as correlations, wavelet transform coherence (WTC), and general linear model (GLM) analysis (Scholkmann et al., 2013; Tachtsidis and Scholkmann, 2016). Typically, those methodologies are applied to investigate the interbrain synchronization (IBS) between the neural signals of the dyads executing cooperation or competition tasks such as the one performed by Cui and Reiss (2012) and Babiloni and Astolfi (2012). For example, two out of the five studies of brain synchronization applied correlations analysis between the oxyhemoglobin (HBO_2) time series of teachers and students (Holper et al., 2013; Takeuchi et al., 2017). The other three applied the WTC to the hemodynamic measurements to estimate the IBS of teachers and students (Pan et al., 2018; Zheng et al., 2018, 2020). However, the advance of computational processing power and machine learning techniques has allowed alternative methods to provide a deeper understanding of the neural mechanisms underlying such complex processes.

In this proof-of-concept study, we aim to contribute to the methodological field of hyperscanning data analyses. We attempted to predict the brain of one subject using the other subjects' brain signals as predictors. We chose the teacher-student interaction to illustrate the usefulness of this methodology according to the prediction-transmission hypothesis. We intended to find hemodynamic correlates that might be related to this hypothesis. We exploit the possibility of predicting a student's brain hemodynamic response using the teacher's hemodynamic signals as predictors. We applied two regression models, the support vector regression (SVR) and the ordinary least square (OLS) to the HBO_2 from the PFC and temporal-parietal junction (TPJ) of teachers and preschoolers realizing a teaching-learning task.

METHODS

Participants

We collected brain signals from eight healthy pairs of teacher-student. Four adults (two males) age from 21 to 28 years; eight children (four boys) aged between 3 and 5 participated in the experiment. Children were recruited by advertisements in a public school close to the university where the experiment was performed. The teachers were tutors from a Science Museum at the University of São Paulo. Three pairs of subjects were excluded due to difficulties during data acquisition, either due to the inability to follow the experimental task or sensor signal unusable in at least one dyad participant. A local ethics committee approved the research, and all participants (teachers and children's parents) signed a written consent form.

Experimental Task

The experimental task aims to emulate the teacher-student interaction as described in Brockington et al. (2018). In this task, the teacher presents the mechanisms to sum two numbers by playing a space-race game with the student. The teacher certified that the child could count from 1 to 12 and then explained how to add two natural numbers using matchsticks. They began the race by throwing two dice of six faces, the player who got the highest sum of the outcomes from the two dice started the game. They continued the race by walking the steps according to the sum of the dice numbers. All dyads performed the same task. It was a continued task without a resting period and lasted around 15 min per dyad.

fNIRS Acquisition and Preprocessing

We used a NIRScout (NIRx Medical Technologies, New York, NY, United States) sampling rate of 7.81 Hz device, with 16 sources and 16 detectors to simultaneously collect the teachers' and students' hemodynamics brain data. For each participant, optodes were positioned in the PFC (channels from 1 to 8) and the TPJ (channels from 9 to 18), **Figure 1**. The first was chosen because it is involved with executive functions related to counting and simple mathematical operations (Artemenko et al., 2018). The second is related to social features such as empathy and memorization (Brockington et al., 2018). The data was collected using NIRSTAR acquisition software. We preprocessed the fNIRS signals to reduce the effects of artifacts. First, we made a visual inspection to detect signals irregularities that could be related to artifacts or data collection problems. Data with irregularities such as missing channels and saturated values were discarded. Second, we applied a bandpass filter (0.01 Hz < freq. < 0.2 Hz) on the raw data to remove low-frequency systemic artifacts and cardiac and respiratory cycles. We then calculated the HBO_2 variations by using the modified Beer-Lambert law with the whole time series as a baseline and differential path lengths (DPF) 7.25 and 6.38 for the wavelengths of 760 and 850 nm, respectively. Calculations were performed with a home-made MATLAB script from our research group.

The Predictive Models

We used two regression models to predict the signals of students using the teachers' signals as predictors. The first is the SVR, an approach used to create predictive models for continuous data. One of SVR's advantages is the power to treat high dimensionality and multicollinearity data, providing greater prediction of unseen data (Awad and Khanna, 2015). The second is the traditional OLS, a more conservative approach that requires assumptions such as homoscedasticity and the absence of the residuals' autocorrelation. These assumptions may not always be satisfied with fNIRS signals (Huppert, 2016).

Several studies of ML and fNIRS have demonstrated that model's accuracy is higher when using HBO_2 signals to classification and prediction models (Bogler et al., 2014; Song et al., 2016; Liu and Ayaz, 2018; Rojas et al., 2019). Therefore, the predictive models were performed over the HBO_2 signals of students S_i and teachers T_i,with i = 1,2,3...0.18 (number of fNIRS channels). We considered the whole task in the analysis, which is approximately 7,000 time-points (∼15 min × 7.81). We trained the models with the first 50% of the data $\{S_i^{tr}, T_i^{tr}\}$, and the other 50% $\{S_i^{ts}, T_i^{ts}\}$ was used for prediction (i.e., testing the models' performance). For each pair of student-teacher, the SVR (with linear kernel) and OLS multivariate models were built with the student's data from each channel j = 1,2,3...18 being the response variable, and the signals of the 18 teacher's channels the predictors (Equation 1). It gave us one model for each fNIRS channel, resulting 18 models per student-teacher pair with prediction performed *via* SVR, and 18 models predicting *via* OLS. We applied them to the teachers' test T_i^{ts}data to predict the students' signals S_i^{pr} (Equation 2).

$$S_j^{tr} = \sum_{i=1}^{18}(w_i * T_i^{tr}) + b \quad (1)$$

$$S_j^{Pr} = \sum_{i=1}^{18}(w_i * T_i^{ts}) + b \quad (2)$$

As the accuracy metric, we computed the Spearman correlation coefficient (which is robust against outliers) between the predicted S_i^{pr} and the test S_i^{ts} signals of the students, for each fNIRS channel. We tested the statistical significance of the correlation *via* a null distribution built by using a bootstrap approach (see **Figure 2**). We first found the lag in which the autocorrelation of the teacher's HBO_2 time-series were close to zero. The lag varied for each teacher-student dyad being (35, 37, 30, 51, and 83 points), for the respective dyads (1,2,3,4,5). We used this value to truncate the teacher's time series in blocks, following the rule $number\ of\ blocks = \frac{time\ series\ length}{lag}$. The blocks were shuffled and rebound. This procedure minimized the temporal dependency between the teachers' and students' signals. The training, predicting, and testing modeling were repeated 1,000 times with the teacher's resampled HBO_2 signals as the predictors; and a null distribution of the correlations coefficients was built. The p-value was calculated as the ratio between the values computed with bootstrapped data higher than the calculated with original signals, and the total number of coefficients computed with bootstrapped data. The SVR computations were performed using the package e1071 of the R software (Meyer et al., 2019). A scheme describing the procedure is depicted in **Figure 2**.

RESULTS

The student's signals predicted with the SVR model S_j^{Pr}were statistically significantly correlated with the measured test data recordings $S_i^{ts}$for all five teacher-student dyads, for a significance level of 0.01 (**Figure 3A**). A few channels lost their significant results after a false discovery rate (FDR) correction. Considering the uncorrected values, we found correlations in the signals from different channels located in the TPJ. All dyads had at least two signals from channels of this region correlated with predicted

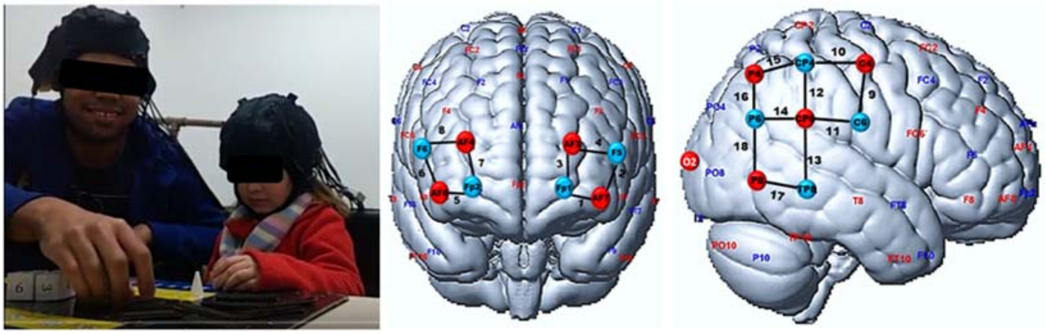

FIGURE 1 | fNIRS montage. **(**Left) Participants during an experiment with fNIRS sensors attached (Middle and Right). fNIRS cortical measurement locations visualized on the brain surface, on prefrontal and temporal-parietal cortices. Red and blue circles represent light sources and detectors, respectively. EEG 10—10 international system positions are also depicted. The black lines and numbers are the fNIRS channels. The same montage was used for both student and teacher heads.

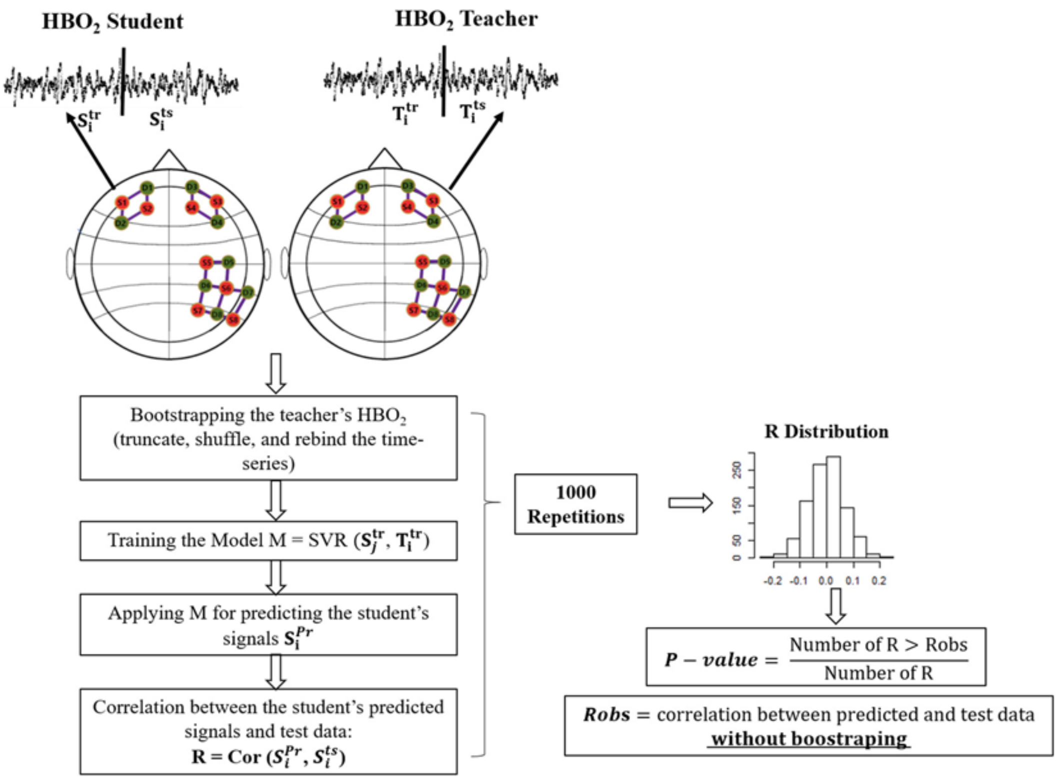

FIGURE 2 | Scheme of the bootstrapping approach. The two circles depict the student and teacher's head. Green and orange circles represent the fNIRS sources and detectors. Full lines represent channels. For simplicity, we only include the SVR in this picture (Training the Model). However, the procedure with OLS is analogous.

signals. For instance, signals from channels 11 and 15 of dyad I, channels 9 and 16 of dyad III, channels 9 and 10 of dyads IV, and channels 13 and 15 of dyad V showed these results. Dyad II had signals from almost all channels (9,10,11,12,13,16, and 17) of the TPJ associated with the predicted data; the only exception was the channels 14,15 and 18. The SVR predictions of signals from the prefrontal cortex were significantly correlated to the test data of dyad II and V. These results were verified in almost all channels of both dyads, except for channels 1 and 3 of dyad II; see **Table 1**. However, for the correlation corrected values (FDR, significance level = 0.01), dyads II and V kept the significant results, while the few outcomes related to dyads I, III, and IV lost the statistical significance.

On the other hand, only a few predictions performed with OLS showed significant results, for a significance level of 0.01 (**Figure 3B**). Predicted signals of the prefrontal cortex (channel

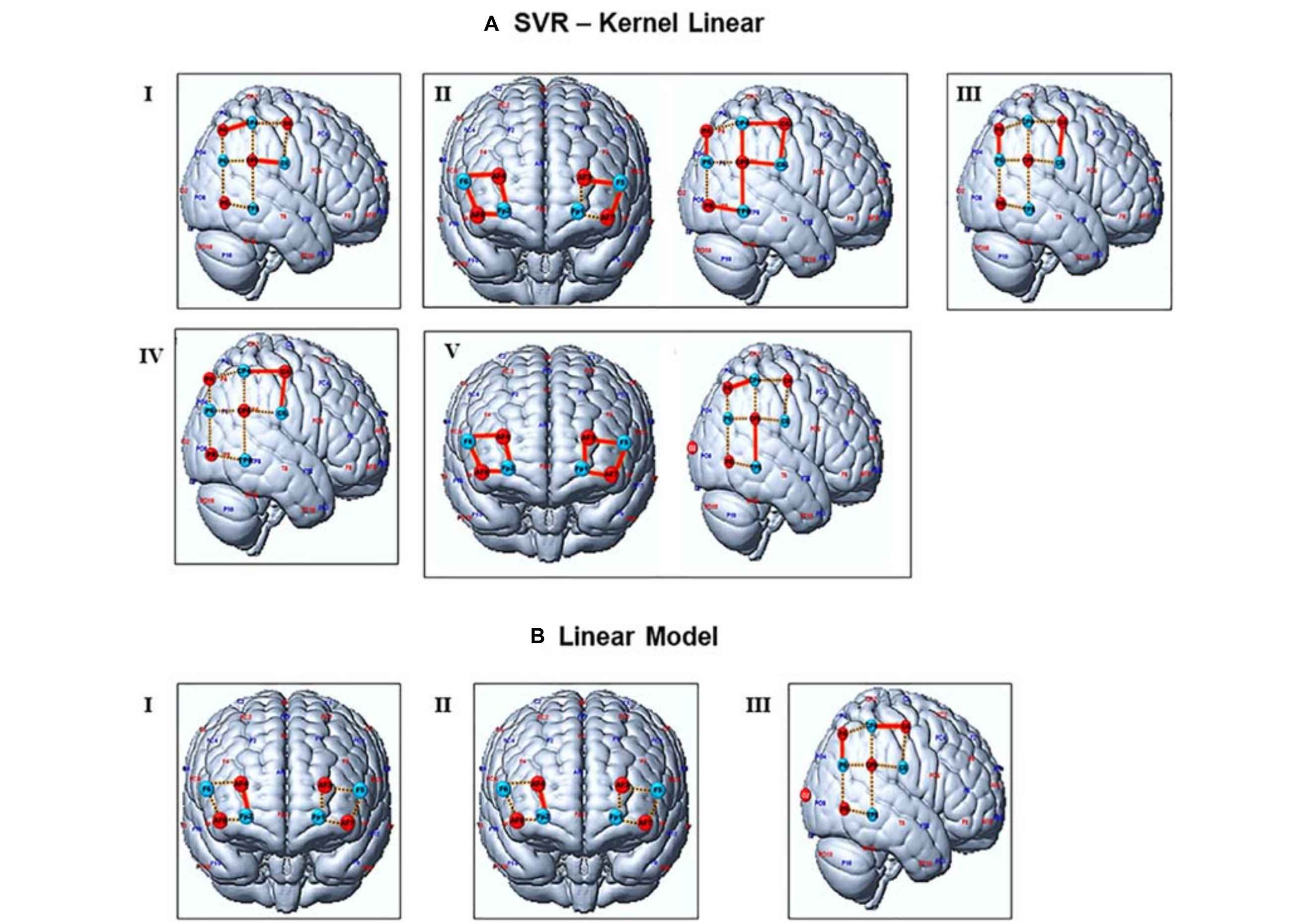

FIGURE 3 | Representation of channels with significant signal's predictions. **(A,B)** depict the channels predicted by the SVR and OLS models, respectively. Red lines represent channels with a statistically significant correlation between test and predicted data (without FDR corrections). Channels with significant outcomes after FDR corrections are presented in bold letters at **Table 1**. Dashed yellow represents the general channels. Blue and red circles are the source and detectors. Numbers from I to V represent the student-teacher dyads.

7) from pairs I and II were statically significantly correlated with the real data, while pair III showed this outcome in channels 10 and 16 from the TPJ. The OLS predictions showed significant associations with real data only in three out of five pairs of subjects, while SVR predicted associations for all pairs of however, the statistical significance of these results does not survive after the FDR correction.

Some channels showed negative correlations between SVR/OLS predictions and test data. However, these values are not statistically significant. The Spearman coefficients of correlations between OLS and SVR predictions and test data, with their corrected and uncorrected *p*-values, are shown in the **Supplementary Material**. **Tables 2** and **3**, respectively.

DISCUSSION

This study aimed to test whether the teachers' signals can predict a students' brain hemodynamic. We applied the machine learning algorithm SVR and compared the results with predictions performed *via* the traditional OLS. The SVR yielded significant results for all dyads, while OLS presented statistically significant correlations with the test data of only two. The results with SVR and the OLS differed in the number of dyads and fNIRS channels. SVR predicted a total of 29/90 signals across the five pairs of individuals (18 channels x 5 dyads = 90 signals), while OLS predicted only 4/90. When considering multiple corrections, these numbers go to 23/90 for the SVR, and no significant results for OLS.

The fact that SVR predicted more statistically significant results than the OLS might be explained by the conceptualization of its estimator. It follows the principle of maximal margin. It does not care about the prediction as long as the error is less than , which is the highest deviation of the prediction function $f(x)$ from the target value y_i. These features, combined with the fact that the cost parameter can penalize the regression, provide the SVR power to avoid over-fitting and give more generalization to the test data (Smola and Schölkopf, 2004; Awad and Khanna, 2015). These finds are supported by other studies that used SVR to predict hemodynamic brain signals. For instance, Liu et al. (2015) argued that SVR is more suitable than OLS to predict human deep-brain regions' activity using fNIRS since

TABLE 1 | Correlation between SVR and OLS predictions and test data.

Channel	Dyad I	Dyad II	Dyad III	Dyad IV	Dyad V
1					**0.25****
2		**0.28****			**0.23***
3					**0.30****
4		**0.26****			0.18*
5		**0.31****			**0.36****
6		**0.18***			**0.22***
7	0.12* (OLS)	**0.17*** 0.14* (OLS)			**0.33****
8		**0.24****			**0.19***
9		**0.29****	0.15*	0.17*	
10		**0.31****	0.23* (OLS)	0.22*	
11	0.18*	0.30**			
12		**0.23****			
13		**0.23****			
15	0.15*				**0.21***
16		**0.28****	0.16* 0.20* (OLS)		
17		**0.30****			

*Spearman coefficients of correlations between the signals predicted and test data. The OLS predictions have the abbreviation (OLS) next to the value of correlation. Only statistically significant results are presented; ** p-value ≤ 0.001; *p-value ≤ 0.01. Bold letters represent channels with significant outcomes after FDR corrections.*

TABLE 2 | Spearman Correlation between OLS predictions and Test data.

Ch	Dyad 1			Dyad 2			Dyad 3			Dyad 4			Dyad 5		
	S	P	FDR	S	P	FDR	S	P	FDR	S	P	FDR	S	P	FDR
1	−0.039	0.78	1.00	0.056	0.66	0.89	0.029	0.34	0.50	0.002	0.53	0.92	0.024	0.30	0.94
2	−0.043	0.74	1.00	0.041	0.32	0.89	0.156	0.04	0.13	0.067	0.25	0.92	−0.133	0.80	0.94
3	−0.036	0.60	1.00	−0.026	0.79	0.89	0.053	0.06	0.17	0.101	0.21	0.92	−0.064	0.47	0.94
4	−0.075	0.93	1.00	−0.026	0.70	0.89	0.111	0.23	0.46	0.069	0.31	0.92	−0.110	0.62	0.94
5	−0.008	0.33	1.00	0.081	0.07	0.62	0.157	0.03	0.13	−0.074	0.37	0.92	−0.147	0.92	0.94
6	−0.062	0.86	1.00	−0.038	0.50	0.89	−0.043	0.84	0.89	0.007	0.46	0.92	−0.152	0.90	0.94
7	0.117	0.01	0.13	0.140	<0.01	0.05	0.030	0.36	0.50	−0.037	0.33	0.92	−0.173	0.90	0.94
8	0.031	0.30	1.00	−0.058	0.51	0.89	0.016	0.75	0.84	−0.165	0.97	0.97	−0.124	0.85	0.94
9	−0.110	0.90	1.00	−0.077	0.76	0.89	0.039	0.43	0.52	−0.070	0.75	0.97	−0.193	0.91	0.94
10	0.005	0.30	1.00	−0.026	0.44	0.89	0.226	<0.01	0.04	0.156	0.10	0.92	−0.022	0.36	0.94
11	−0.125	0.97	1.00	0.021	0.49	0.89	0.149	0.10	0.24	−0.132	0.92	0.97	−0.130	0.94	0.94
12	−0.193	0.95	1.00	−0.048	0.49	0.89	0.179	0.03	0.13	−0.104	0.96	0.97	−0.103	0.82	0.94
13	−0.030	0.69	1.00	−0.068	0.77	0.89	−0.229	1.00	1.00	−0.080	0.81	0.97	−0.061	0.60	0.94
14	−0.086	0.80	1.00	0.011	0.56	0.89	−0.013	0.37	0.50	−0.052	0.56	0.92	−0.036	0.36	0.94
15	−0.096	0.92	1.00	−0.137	1.00	1.00	0.059	0.26	0.47	−0.097	0.84	0.97	−0.062	0.67	0.94
16	−0.217	1.00	1.00	−0.015	0.60	0.89	0.200	<0.01	0.04	−0.054	0.69	0.97	−0.080	0.87	0.94
17	0.029	0.31	1.00	−0.014	0.49	0.89	0.070	0.39	0.50	0.051	0.26	0.92	−0.088	0.61	0.94
18	−0.012	0.42	1.00	−0.110	0.89	0.94	0.066	0.11	0.24	−0.030	0.48	0.92	−0.106	0.69	0.94

Abbreviations in the table stand for: Ch, Number of the fNIRS Channel; S, Spearman Correlation between the predicted (S_i^{pr}) and the test (S_i^{ts}) signals; P, P-value of the Spearman correlation; FDR, P-value corrected by the False Discovery Rate (FDR); Underlined numbers, P-value ≤ 0.01.

SVR defines the weights to reflect the contributions of the features better than the OLS. Zhang et al. (2014) compared the SVR and OLS application to synthetic data to predict voxel-based lesion-symptom mapping (VLSM). They verified that SVR presented higher sensitivity and specificity for detecting the lesion-behavior relationship than the OLS.

This proof-of-concept study is focused on developing and testing a new methodological approach and not designed to investigate the specific brain areas involved in the teaching-learning process. However, it is relevant to note that all dyads showed a relationship between training and testing data of the TPJ, a brain area known to be involved in social cognition and processes underlying empathy and social interactions (Zheng et al., 2018). For instance, Zheng et al. (2018) found that interpersonal neural synchronization (INS) between the student's and teacher's TPJ varied with the teaching strategy; an increase of

TABLE 3 | Correlation between SVR predictions and Test data.

Ch	Dyad 1			Dyad 2			Dyad 3			Dyad 4			Dyad 5		
	S	P	FDR	S	P	FDR	S	P	FDR	S	P	FDR	S	P	FDR
1	−0.010	0.57	0.72	0.083	0.14	0.17	0.094	0.06	0.18	0.139	0.04	0.162	0.246	<0.01	0.00
2	−0.090	0.91	0.91	0.283	<0.01	0.00	−0.004	0.51	0.66	0.072	0.20	0.321	0.228	<0.01	0.01
3	−0.012	0.60	0.72	−0.007	0.55	0.58	0.057	0.22	0.42	0.088	0.13	0.299	0.294	<0.01	0.00
4	0.031	0.30	0.68	0.262	<0.01	0.00	−0.007	0.52	0.66	0.109	0.10	0.255	0.178	0.01	0.02
5	0.005	0.50	0.70	0.311	<0.01	0.00	0.068	0.16	0.35	−0.087	0.89	0.94	0.360	<0.01	0.00
6	−0.067	0.86	0.91	0.185	<0.01	0.00	0.092	0.08	0.20	0.139	0.05	0.162	0.216	<0.01	0.01
7	0.013	0.46	0.70	0.174	0.01	0.01	−0.055	0.80	0.84	0.078	0.17	0.321	0.331	<0.01	0.00
8	0.022	0.39	0.70	0.236	<0.01	0.00	0.031	0.32	0.53	0.057	0.21	0.321	0.195	<0.01	0.01
9	0.120	0.04	0.26	0.293	<0.01	0.00	0.154	0.01	0.11	0.171	0.01	0.108	0.061	0.21	0.27
10	0.016	0.42	0.70	0.309	<0.01	0.00	−0.039	0.73	0.82	0.219	<0.01	0.036	0.060	0.23	0.27
11	0.176	0.01	0.06	0.300	<0.01	0.00	−0.234	1.00	1.00	−0.040	0.70	0.791	−0.276	1.00	1.00
12	0.044	0.22	0.67	0.228	<0.01	0.00	0.113	0.04	0.18	0.056	0.20	0.321	0.127	0.04	0.07
13	0.080	0.12	0.43	0.232	<0.01	0.00	0.113	0.06	0.18	−0.023	0.62	0.745	0.099	0.10	0.15
14	0.000	0.50	0.70	0.067	0.15	0.18	0.132	0.03	0.17	−0.152	0.98	0.979	0.009	0.46	0.52
15	0.152	0.01	0.06	−0.024	0.64	0.64	0.044	0.23	0.42	0.034	0.35	0.485	0.215	<0.01	0.01
16	0.090	0.09	0.42	0.276	<0.01	0.00	0.161	<0.01	0.05	0.004	0.50	0.638	−0.025	0.64	0.68
17	0.036	0.30	0.68	0.301	<0.01	0.00	−0.011	0.59	0.71	0.109	0.09	0.255	0.064	0.21	0.27
18	−0.033	0.70	0.79	0.032	0.30	0.34	0.007	0.45	0.66	0.138	0.03	0.162	0.159	0.02	0.04

Abbreviations in the table stand for: Ch, Number of the fNIRS Channel; S, Spearman Correlation between the predicted (S_i^{pr}) and the test (S_i^{ts}) signals; P, P-value of the Spearman correlation; FDR, P-value corrected by the False Discovery Rate (FDR); Underlined numbers, P-value ≤ 0.01.

INS between the right TPJ of the teacher and anterior superior temporal cortex of the student was associated to better teaching outcome. The fMRI study about predictions of human decisions in a poker game showed that signals from the TPJ provided unique information about the upcoming decision (Carter et al., 2013). Based on that, our finds give evidence to confirm that this region plays a fundamental role in the cognition process underlying student-teacher interaction.

On the other hand, only two out of the five pairs presented statistically significant correlations between training and test data from the pre-frontal cortex. This area is related to the cognitive process related to learning and has been evaluated with fNIRS in diverse tasks before (Wood and Grafman, 2003; Ayaz et al., 2012; Singh et al., 2018; Nozawa et al., 2019). Additionally, when performing the task, the dyads recruits several executive functions such as attention and inhibitory control during the verbal communication. Those functions are related to the PFC activity (Gvirts and Perlmutter, 2020; Kelsen et al., 2020). Furthermore, considering that our task consists of a teaching-learning process of adding two numbers less or equal to six, the discrepant results across the dyads might be explained by the differences in the cognitive workload of each child performing the task. It may require different engagement levels with the teachers for learning how to add the numbers leading to the different results found here (Sun et al., 2020; Zhang et al., 2020).

Some limitations must be considered in this study. The sample size is small so that more studies with a higher number of participants are necessary regarding the generalization of the results. We did not have 3D-digitizers to map the optodes locations on the participants' heads. The use of 3D-digitizers in Pinti et al. (2019) follow-up study could add more information for comparing homologous brain areas and homogeneity of the regions across subjects. Although short-channels data contribute to reducing physiological noise, we did not perform this measurement due to our fNIRS device limitations. Nonetheless, we tried to reduce those effects by applying filters to our data (Yücel et al., 2021). We adopted the conservative band-pass approach to filter the fNIRS data and avoid excessive modifications in the signals, which could mask relevant aspects during the prediction procedures. This choice was made because different filtering methods might interfere with the outcomes (Huppert, 2016; Pinti et al., 2019). While we applied band-pass filter to reduce the physiological noise, the fNIRS signal can be still confounded by motion artifacts. Therefore, other filters might be useful according to the features of the data (Brigadoi et al., 2014). Additionally, given the limited number of sensors, we could only investigate cortical regions within the prefrontal and right TPJ regions. Nevertheless, other areas may also play a role in the teacher-student interaction, and future studies may explore other cortical areas with high-density sensors. Also, fNIRS provides information about cortical areas, restricting the investigation of subcortical regions that may also be relevant to the teacher-student interaction (Kostorz et al., 2020). Additional physiological signals have been shown not to contribute to the mental state decoding (Liu et al., 2017). However, such signals (e.g., heart rate, heart rate variability, and skin conductance) could bring relevant information about the participant's arousal in this context and contribute to the prediction model.

Our proposed methodology demonstrated the possibility of using the teacher's fNIRS signals to predict the student's brain hemodynamic response. According to previous work, teaching outcomes are improved according to the teacher-student brain synchronization, and it is theoretically supported by the prediction-transmission hypothesis (Kline, 2015; Zheng et al., 2018). Preliminary results suggest that our proposed approach can be used to better understand the brain synchronization during the teacher-student interaction in which, speculatively, the teacher and student behaviors may be continuously updated according to their brain state predictions. Regardless, future research with a larger sample size and a broader number of fNIRS should continue to investigate which brain areas of the teacher are related to the students' brain prediction. It can be achieved by considering the weights/contribution of each channel in teacher's cohort in/to predicting student's brain response. It will add more information about the neural mechanisms underlying the teaching-learning process and give experimental evidence for theoretical frameworks such as the prediction-transmission hypothesis.

DATA AVAILABILITY STATEMENT

The datasets presented in this article are not readily available because the ethics committee did not permit the sharing of data. Requests to access the datasets should be directed to JS, joao.sato@ufabc.edu.br.

ETHICS STATEMENT

The studies involving human participants were reviewed and approved by Comite de Etica em Pesquisa (CEP)—Universidade Federal do ABC, SP-Brazil. Written informed consent to participate in this study was provided by the participants' legal guardian/next of kin. Written informed consent was obtained from the individual(s), and minor(s)' legal guardian/next of kin, for the publication of any potentially identifiable images or data included in this article.

AUTHOR CONTRIBUTIONS

CB collected, analyzed the data, and wrote the manuscript. GAB participated in the conception of the experiment and data collection. GB participated in the conception of the experiment and data collection. HA revised and contributed to improving the quality of the manuscript. JS conceived the experiment, supervised the data collection and analysis, revised the manuscript, and contributed to improving the quality of the manuscript. All authors contributed to the article and approved the submitted version.

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SUPPLEMENTARY MATERIAL

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Tiered Neuroscience and Mental Health Professional Development in Liberia Improves Teacher Self-Efficacy, Self-Responsibility, and Motivation

Kara Brick[1,2], Janice L. Cooper[1], Leona Mason[1], Sangay Faeflen[3], Josiah Monmia[1] and Janet M. Dubinsky[4]*

[1] The Carter Center Mental Health Program, Monrovia, Liberia, [2] Peace Corps Liberia, Monrovia, Liberia, [3] Ministry of Education, Monrovia, Liberia, [4] Department of Neuroscience, University of Minnesota, Minneapolis, MN, United States

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Analía Arévalo, University of São Paulo, Brazil

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***Correspondence:**
Janet M. Dubinsky
Dubin001@umn.edu

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After acquiring knowledge of the neuroscience of learning, memory, stress and emotions, teachers incorporate more cognitive engagement and student-centered practices into their lessons. However, the role understanding neuroscience plays in teachers own affective and motivational competencies has not yet been investigated. The goal of this study was to investigate how learning neuroscience effected teachers' self-efficacy, beliefs in their ability to teach effectively, self-responsibility and other components of teacher motivation. A pilot training-of-trainers program was designed and delivered in Liberia combining basic neuroscience with information on social, emotional, behavioral and mental health issues faced by students. Tier I of the professional development was a 2 weeks workshop led by a visiting neuroscientist. A subset of the 24 Tier I secondary science teachers formed a Leadership Team who adapted the content to the Liberian context and subsequently led additional workshops and follow-up sessions for the Tier II secondary science teachers. Science teachers in both tiers completed the affective-motivational scales from the internationally vetted, multiscale Innovative Teaching for Effective Learning Teacher Knowledge Survey from the OECD. Tier II teachers completed the survey in a pre-post-delayed post design. Tier I teachers completed the survey after the workshop with their attitudes at that time and separately with retrospective projections of their pre-workshop attitudes. Ten of the 92 Tier II teachers participated in structured interviews at follow-up. Statistical analysis of survey data demonstrated improved teacher self-efficacy, self-responsibility for student outcomes, and motivation to teach. Qualitatively, teachers expressed more confidence in their ability to motivate students, engage them through active learning, and manage the class through positive rather than negative reinforcement. Teachers' own self-regulation improved as they made efforts to build supporting relationships with students. Together, these results demonstrated that (i) teacher affective-motivational attitudes can be altered with professional development, (ii) basic neuroscience, as knowledge of how students learn, can improve teacher competency, and (iii) a training-of-trainers model can be effective in a low and middle income country for disseminating neuroscience knowledge, increasing teachers' knowledge of students' social and emotional needs, and promoting educational improvement.

Keywords: neuroeducation, teacher professional development, teacher self-efficacy, teacher self-responsibility, teacher motivation, affective and motivational attitudes, teacher competencies, mental health literacy

INTRODUCTION

Seminally, Shulman (1987) divided the knowledge base needed by teachers into seven categories: content knowledge, general pedagogical knowledge, pedagogical content knowledge, curricular knowledge, knowledge of learners and their characteristics, knowledge of educational systems and contexts, and knowledge of educational theories and philosophy. Regarding knowledge of learners, Shulman (1986) states "aspects of physiology are apparently deemed necessary because of the expectation that teachers understand the biological functioning of their pupils." Neuroscience provides teachers with knowledge about how learning occurs in the brain, a topic that falls within the knowledge of students category. More recently, neuroscience was recognized as providing fundamental contributions to knowledge of the learning processes and knowledge of individual student characteristics (Voss et al., 2011). Knowledge of learning processes encompasses understanding memory and information processing, cognitive development, motivation and attention—elements of contemporary neuroscience (Posner and Rothbart, 2007; Voss et al., 2011). Knowledge of individual student characteristics includes specific learning disabilities, such as ADHD, with defined neurobiological bases (MTA Cooperative Group, 1999; Voss et al., 2011). Neuroscience provides a biological basis for how learning occurs in the brain and as such should function to inform theories of learning (Meltzoff et al., 2009; Ansari et al., 2017). Indeed, calls have been made to make neuroscience a part of pre-service teacher education and in-service professional development as part of teachers' knowledge of students, where it compliments theories of learning from cognitive science and psychology (Dubinsky et al., 2013; Ansari et al., 2017).

Professional development in neuroscience has been demonstrated to increase teacher content knowledge as well as confidence in and use of student-centered pedagogy (MacNabb et al., 2006b; Roehrig et al., 2012). This was true for science teachers and non-science teachers (Schwartz et al., 2019). After attending a series of neuroscience seminars, teachers embraced the content as relevant to their practices (Dommett et al., 2011). Even a short 90 min exposure to neuroscience ideas may produce changes in teachers' intended classroom practices (Howard-Jones et al., 2020). Prior data (Dubinsky et al., 2019) suggest teachers' may also provide students with more social and emotional support following neuroscience professional development (PD), but this has not been studied explicitly. Thus, knowledge of how learning occurs in the brain has the power to influence teachers' thinking about their students and practices. However, the effect of neuroscience training upon established measures of teacher competence have not been previously reported.

Teacher's competence has been described to "comprise all the required cognitive knowledge for creating effective teaching and learning environments" (Guerriero, 2017b). The international Innovative Teaching for Effective Learning (ITEL) project was designed to assess in-service and pre-service teachers' professional qualities (Baumert and Kunter, 2013; Blomeke, 2017; Sonmark et al., 2017). ITEL expanded upon Shulman's (1986, 1987) ideas and conceptualized teachers' competence as falling into the three broad areas; pedagogical knowledge, opportunities to learn, and affective-motivational attitudes (Guerriero and Revai, 2017; Sonmark et al., 2017). These broader competencies incorporated ideas that go beyond pedagogy and content to address teacher attitudes toward their own learning, motivations and aptitudes (Blomeke, 2017). Teacher competencies and classroom actions are both cognitive, knowledge based and affective, intuitive, and goal driven (affective-motivational) (Blomeke, 2017; Sonmark et al., 2017). The context-dependent choices teachers make are based upon their beliefs about both teaching and their own abilities (Sonmark et al., 2017). Teachers' own emotional or affective states become central to the process of encouraging and optimizing student learning (Sonmark et al., 2017). Teachers' social and emotional behaviors set the tone for classrooms. Poor social-emotional skills can exacerbate poor student outcomes while teachers who are competent in these areas can effectively promote social, emotional and intellectual learning among their students (Osher et al., 2012). The ITEL project teacher knowledge survey (ITEL-TKS), based upon these competency dimensions, incorporated many previously developed constructs measuring teacher characteristics (Sonmark et al., 2017). ITEL-TKS operationalized the affective-motivational dimension with scales exploring teacher self-efficacy (TSE), self-responsibility, personal motivation and commitment to teach, goals, and beliefs about instruction and classroom management (Sonmark et al., 2017). As an internationally validated instrument, the ITEL-TKS framework and affective-motivational scales were selected for use in the current study of the effect of neuroscience PD.

The influence of neuroscience on a range of teachers' attitudes was studied as part of a training program combining neuroscience and mental health (MH) education to secondary science teachers in Liberia. The program's intent was to improve teachers' ability to recognize and support students with social, emotional, behavioral or mental health issues. We reasoned that the MH content would be best understood after building a foundational knowledge of how the brain worked. The workshop had two main goals. The first was to influence teachers' attitudes toward persons with MH concerns by providing the background needed to understand student MH issues and to provide referrals to local MH clinicians (Weist et al., 2017). The effects of the combined training on teachers' attitudes toward mental illness (MI) appear elsewhere (Brick et al., 2021). The second goal was to promote teacher beliefs about their abilities to motivate, engage and involve students in active learning, as aligned with the goals for Education for Sustainable Development (Ahmad et al., 2018; Education 2030, 2018). The latter goal required providing teachers with knowledge about the workings of the brain, a subset of the broader category of knowledge of students. This paper focuses on how the combined neuroscience and MH training may have altered teacher affective and motivational attitudes toward their perceived ability to reach and engage students.

To that end, a professional development program was designed and piloted to provide Liberian secondary science teachers with an intellectual foundation for understanding student social, emotional and behavioral needs combined with modeling of inclusive pedagogical practices. The content focus was neuroscience, content included in the Liberian secondary school curriculum that would also advance interest in STEM, a stated economic need for African development (African Development and Bank, 2020). On a theoretical level, neuroscience and MH were viewed as part of knowledge of students (Shulman, 1987). The MH portion of the intervention was designed to promote teacher recognition of and response to social, emotional and behavioral student issues (Pacione and Cooper, 2014). In this frame, the workshops were designed to influence teachers' professional competence in the affective-motivational aspects of their overall teaching (Guerriero, 2017a).

Understanding both the neuroscience of learning and memory and students' social, emotional and behavioral issues comprise different aspects of knowledge of students and their characteristics. As such, this information would be expected to influence teachers' self-efficacy (TSE), their attitudes and beliefs around instructional strategies, classroom management, and student engagement. Viewing TSE within the larger dimension of teacher affective-motivational attitudes (Sonmark et al., 2017), the current study examines how this PD altered teachers' own attitudes, including their beliefs, self-efficacy and motivation for teaching. A priori, there were no expectations that other components of the affective-motivational attitudes, besides TSE, would be altered. Both qualitative and quantitative approaches were employed to analyze how science teachers in a low and middle income country (LMIC) responded to a combined neuroscience and MH PD workshop. The workshops were structured as a training-of-trainers model so that the majority of teachers would be trained by their Liberian peers, seeding local communities of practice (Westbrook et al., 2013; Kohrt et al., 2015; Chikunda, 2018). The specific research questions were:

(1) What was the fidelity of the Tier I to Tier II intervention?
(2) Did Tier I and Tier II teachers learn neuroscience sufficiently to become confident in that knowledge?
(3) How did both Tier I and Tier II trainings effect teacher affective-motivational attitudes?

MATERIALS AND METHODS

A mixed methods approach was used to assess the efficacy of a training-of-trainers PD program in neuroscience and mental health for Liberian secondary science teachers. Quantitative survey data was collected from teachers in both tiers regarding their confidence in their knowledge of neuroscience and their affective and motivational attitudes toward teaching. Qualitative data from structured interviews was collected from a subset of Tier II teachers on how they applied this knowledge in their practices.

The Liberian Context

Liberian teachers have unmet emotional needs from traumas suffered in the civil war (1989–2003) and the Ebola epidemic (2013–15). In Liberian culture, teachers assume multiple roles beyond implementing the curriculum: acting as counselors, builders of the peace, medical personnel and psychologists (Adebayo, 2019). Administrators acknowledge these Herculean expectations but have not provided strategies or training to accomplish all these tasks (Adebayo, 2019). Education lost much of its resources, and subsequently value during the civil war. PD provides tangible, emotional support for teachers, validates their worth, and improves their skills to handle the social, emotional and intellectual needs of their students (Westbrook et al., 2013). What remains to be determined is how to deliver effective PD that combines content with training on social-emotional development and inclusive teaching practices in a low-resource environment.

Improving teacher quality through ongoing PD remains a key ingredient for addressing the educational inadequacies in Liberia (Fashina, 2017). During early post-civil war years, some teacher training programs emphasized active learning classroom strategies, but how widespread this process was or continues to be has not been documented (Barrios-Tao et al., 2017). The principle focus from international PD efforts has been on raising reading rates through elementary school teacher training (King et al., 2015; Gove et al., 2017). Examination of effective teaching practices across LMICs revealed that improving teacher communication encourages interactive pedagogies that increase student learning outcomes (Westbrook et al., 2013). Specific strategies include supporting students with feedback in a safe environment and relating content to local contexts and experiences. Group work, discussions, questioning, demonstrations, explanations, use of models and materials beyond the textbook, and use of local languages were identified as effective practices within these strategies. A key finding in this study was the need to align teacher education and PD to promote widespread use of these pedagogical practices (Westbrook et al., 2013). For secondary teachers in Liberia, the limited, available PD has been provided mostly by NGOs, with internal evaluations subject to Ministry of Education and donor requirements.

Program Description

This pilot project was designed to train a cadre of Liberian science teachers in the neurobiology of learning and memory, emotional processing and stress, and the etiology of epilepsy and PTSD using best pedagogical practices (Darling-Hammond et al., 2017) and lessons designed for high school classrooms (Dubinsky et al., 2019). In this two tiered plan, a visiting neuroscientist delivered a 2 weeks workshop for Tier I teachers who then adopted the material for the Liberian context, delivered a series of 1 week workshops and trained additional Tier II Liberian teachers. The training-of-trainers model was selected for its ability to leverage existing local community knowledge and assets (Kutcher et al., 2016). Similar training-of-trainers models had been used in prior programs (Kohrt et al., 2018). Tier I training occurred in August 2018, and was comparable to a successful neuroscience teacher PD program in the United States (MacNabb et al., 2006b; Roehrig et al., 2012; Dubinsky et al., 2019; Schwartz et al., 2019). Lessons plans and resources used in the workshop were drawn mainly from open internet neuroscience resources (MacNabb et al., 2006a; SFN, 2019), as recommended for educational improvement in Sub-Saharan Africa (Wolfenden et al., 2012). The project represents a partnership between The Carter Center Liberia, the Ministry of Education, the Peace Corps Liberia, and local schools.

Content for both tiers included understanding the basic neuroscience of brain function and the dysfunction associated with neurological and mental disorders, modeling student-centered teaching practices including experimentation, and improving the pedagogical expertise and confidence of teachers through reflection and discussion. Tier I teachers engaged in role play and practice teaching as well. Additional content for the Tier II trainings was adopted from the Manuel of School Mental Health for Liberia (Pacione and Cooper, 2014), the Good Schools Toolkit (Devries et al., 2015) and 80 min of appropriate TedTalk and internet videos on neuroscience, recognizing and overcoming MH issues and addiction, and building relationships with students. The curricula addressed three of the five domains established for teacher PD recommended in LMICs; namely, content knowledge (neuroscience), teaching skills (modeled student-centered pedagogies) and classroom management (modeled student engagement) (Ginsburg, 2011; Pacione and Cooper, 2014). The domains of student assessment and professional ethics were not applicable to the current project (Ginsburg, 2011). Detailed content comparisons between the two tiers are presented in Results.

Eight Tier I teachers (chosen based upon knowledge, experience, availability and proximity to Monrovia) formed the Leadership Team to plan and deliver the Tier II workshops. A staff member, an Assistant Minister of Education and a Peace Corps Volunteer with 2 years teaching experience in Liberia served as co-coordinators and members of the Leadership Team. The co-coordinators coached and acted as mentors for the rest of the Leadership Team, wrote a knowledge test, and collected data. The Leadership Team delineated the content in the 5 days intensive Tier II workshops. Three Tier II workshops occurred in Monrovia and one in Kakata during fall of 2018. Based upon teacher feedback, the Leadership Team organized and ran four additional two-day follow-up Refresher sessions at local schools 3–5 months later. Refreshers included a day of practicum teaching plus a day of reflection, discussion of successes and challenges, a virtual question and answer session with the visiting neuroscientist, and collection of further data. Throughout this process, the Leadership Team discussed their own vision for the program and regularly met with representatives of the Ministry of Education for guidance.

Participants

The Tier I workshops were attended by seventeen practicing secondary science teachers and seven master teachers working for the Ministry of Education who focused on science initiatives and training (**Table 1**). Ninety-two secondary science teachers attended the Tier II workshops. In keeping with Liberian traditions and as a gesture of respect and partnership, the Ministry of Education Office of Science Education selected Principals of secondary schools within the Monrovia Consolidated School System and Kakata Government Schools and requested one or two teachers be sent for training. Teachers represented a range of communities, educational backgrounds and experience (**Table 1**). Teacher training institutes were closed or defunct during Liberia's civil wars, with the major teacher training institutes not graduating teachers between 1979 and 2009 (Williams, 2011). Many teachers left Liberia during the war or died. Workshop participants were representative of the current population of secondary school science teachers.

All participants voluntarily and formally consented to be a part of the workshop outcome study, conducted according to IRB protocols approved both by the University of Liberia and Emory University. Teachers were assigned numerical identifiers to use instead of their names on all surveys and assessments.

Survey Instruments

Quantitative data comprised surveys teachers completed to examine changes in their knowledge and attitudes. A pre-post-delayed post design was employed. Qualitative interviews were conducted with a subset of Tier II teachers at one Refresher to further examine how teachers felt about the program and what may have changed in their teaching as a consequence. Survey scales were chosen to examine participants' neuroscience knowledge and their confidence in teaching neuroscience content (MacNabb et al., 2006b). The affective-motivational scales of an internationally vetted instrument, the ITEL-TKS, were chosen to capture TSE and other attitudes and teacher beliefs (Sonmark et al., 2017). A few additional scales were selected from the TALIS project (OECD, 2008). Data collection was incomplete for the following scales which were not reported: TM_ESL Teacher Self Efficacy for Student Learning, TM_PD Professional Development, and TALIS 42 Classroom practices. Tier II teachers completed the surveys at the beginning and end of their workshops and on day two of the Refreshers. Tier I teachers completed the pre assessment at the end of the workshop after they had taken the post-assessment. This constituted a retrospective pre-assessment in which initial attitudes were judged relative to the final attitudes, avoiding initial overconfident self-assessment (Levinson et al., 1990; Bhanji et al., 2012).

TABLE 1 | Participant characteristics.

		Tier I	Tier II
Participants	Total	24	92
	Responded to surveys	24	61
	Male	15	63
	Female	9	29
Age	Mean (SD) range	39.5 (10.3) 23–56	35.6 (9.1) 23–62
County where live	Montserrado*	15	32
	Other	4	14
	Unknown	5	15
Education	Masters	4	1
	Bachelors	15	38
	Rural teacher training institute**	3	13
	High school	2	8
Years teaching	Mean (SD) range	9.2 (4.2) 3–20	8.5 (6.2) 2–32
Other Educational work	Yes	19	45
	Number of years	6.5 (4.4) 2–20	4.7 (3.5) 1–15
	No	5	14
Subjects taught (more than one possible)	Science	19	49
	Math	3	11
	Chemistry	1	1
	Biology	1	3
	Health	1	0
	Other	7	25
Teach in a community in a	Large city > 1,000,000	11	14
	City 100,000—1,000,000	8	28
	Town 15,000–100,000	2	15
	Village or rural area	2	2
	Unknown	1	2
Attended training on Manual of School MH***		1	1

**The capital city of Monrovia, home to one third of the country's population, is in Montserrado County.*
***Rural Teacher Training Institutes provide one-year of training for high school graduates who then proceed to teach (Ginsburg and Arrington, 2015).*
****This is a separate training program on the Liberian adaptation of the WHO Manual of School Mental Health (Pacione and Cooper, 2014; Weist et al., 2017).*

Quantitative Analysis

After reverse coding appropriate items, Likert scale survey responses from each of the 12 scales and their associated subscales were calculated according to the following equation: $X_k = (1/N_i) \sum_i^{Ni} \sum_j^{Nj} x_{ij}$, where X_k represents the mean score on scale k, x_{ij} represents the Likert response of teacher i on item j, N_i represents the number of teachers, and N_j represents the number of items in scale k. Data from all Tier II workshops were aggregated. For all rating scales, the valence has been adjusted so that larger values represent more agreement or greater ability. Comparisons between post and retrospective pre time points for Tier I were made using two-tailed t tests (Graphpad Prism, version 6.1). Comparisons among pre, post and Refresher time points for Tier II data were analyzed using one-way ANOVAs followed by Tukey's multiple comparison post-tests (Graphpad Prism, version 6.1).

Qualitative Analysis

On the second day of one of the Refresher sessions, two Leadership Team members interviewed 10 Tier II teachers. The interviews were conducted in Liberian English using a structured interview protocol. Interview questions explored how teachers viewed their roles, student behavior and MH issues, changes, successes and challenges of their teaching and feedback on the trainings. Conversations were digitally recorded, transcribed and annotated prior to coding. Interviewers kept written field notes.

Interviews were initially coded using NVivo 12. A codebook was developed using a framework analysis approach, including an iterative reading of the interviews to generate codes (Saldana, 2016). Additional codes based on the study objectives were subsequently added. Two authors separately coded all interviews, using the field notes for context. Three authors then iteratively discussed and recoded the data until consensus was reached. Independently, two authors summarized the coded data in written form. These summaries were further discussed, edited and combined until themes emerged and consensus was reached.

RESULTS

Fidelity of the Training

To assess the fidelity of the messages delivered during the Tier II workshop (research question 1), the schedules for the

Tier I and Tier II workshops were compared. Considering the different activities, lectures, discussions, experiments, etc., for each, the Tier II workshops covered approximately 50% of the same material as the Tier I workshop. This includes the majority of neuroscience content, seven active learning exercises, daily reflections on the workshop and discussions of how to apply neuroscience to classroom teaching. For the neuroscience content, the Leadership Team slide presentations were edited by the Tier I instructor who answered questions and coached the presenters by email. Critical content on synaptic function and plasticity, learning and memory, neuronal circuits, cognitive function, emotional processing and decision making were similar. Lectures on brain injury and illness and epigenetics contained less mechanistic detail. Autonomic nervous system and adolescent brain development were covered in internet videos. Two Tier I content lectures had a different focus in Tier II: the introductory lecture shifted from a molecular focus to a review of neuroanatomy and neuronal structure and function. The detailed physiology of the stress response became more of an overview with practical applications regarding class disciplinary activities. The Tier II training added presentations on drugs of abuse, how to recognize behavioral and MH issues in a classroom and how to refer students to the MH clinicians (Pacione and Cooper, 2014; Devries et al., 2015). Additional internet videos illustrated recognizing and dealing with mental health needs for oneself and students through personal stories of resiliency and recovery. Two hands-on activities included in the first two Tier II workshop were subsequently dropped in the remaining Tier II workshops to provide more time for discussions. As a longer training, the Tier I workshop included 3 days of practicum teaching, three demonstration experiments, two more discussions of how to apply neuroscience to education, three additional daily reflections on workshop content, a gallery walk, a concept mapping exercise, and three review games that were not part of Tier II.

The Tier I and II workshops briefly discussed the distinctions between direct and constructivist instructional practices. Student-centered, active pedagogies were modeled in both. Teachers were asked to reflect upon the differences between what they experienced in the PD and how they themselves taught. In the practicums, teachers were given feedback on how they delivered a lesson of their choice. During the Tier II workshops and Refresher sessions, teachers openly discussed pedagogical practices.

Confidence in Neuroscience Knowledge

To be able to teach or apply ideas from neuroscience effectively, teachers need to be confident in that knowledge. This was achieved for both Tier I and II participants. Both Tier I and Tier II teachers demonstrated gains in neuroscience knowledge (Brick et al., 2021). Beyond this knowledge gain, teachers in both cohorts expressed an increased confidence in understanding different neuroscience concepts and their ability to teach neuroscience to others (**Figure 1**). Initial analysis of teacher's daily reflections indicated that they comprehended the neuroscience content covered each day, confirming a basis for their confidence gain.

Measures of Teachers' Affective and Motivational Competency

Teachers in both tiers responded to an extensive survey on various aspects of affective-motivational competencies (Sonmark et al., 2017). Survey scales probed their self-efficacy, motivations for teaching, sense of responsibility and self-assessed instructional quality (**Tables 2**, **3**).

Both Tier I and Tier II teachers significantly increased their self-efficacy ratings as a result of the training (**Figure 2**). For Tier I teachers, this was true of all subscales (**Figure 2A**). For Tier II teachers, significant increases appeared for the student engagement subscale, but not the subscales for instructional strategies and classroom management (**Figure 2B**). In addition, at the Refresher time point for Tier II, the increased self-efficacy ratings were not sustained.

On teachers' personal motivations to teach (TM_M scale), Tier I teachers' ratings significantly increased at the end of the workshop but Tier II teachers' ratings did not increase until the Refresher time point (**Figure 3**). Both tiers of teachers increased their self-assessment that they have the abilities and qualities of a good teacher (Ability Subscale). Changes on the personal motivation scale and subscales largely reflected a decreased variability as the ratings clustered more tightly at the top of the scales with time. This is most clearly demonstrated by Tier II teachers' responses regarding their interest in and liking of a teaching career (Intrinsic Career Values). At the Refresher time point, Tier II teachers also felt that teaching provided a secure, stable career path (Extrinsic Career Values). After the workshop, Tier I teachers agreed more with statements regarding the ability of teachers to contribute to society by positively impacting the next generation (Social Career Values).

One component of motivation is how teachers view their professional responsibilities regarding different aspects of their teaching, ranging from how well they motivate and interact with their students to promoting student performance through quality teaching. Changes on the scale of Teacher Self-Responsibility (TM_SR) were slow to occur. Among Tier I teachers, improvement was registered on the subscales of Relationships with Students at the end of the workshop (**Figure 4A**). For Tier II teachers, improvements on the full scale and all subscales occurred at the Refresher time point (**Figure 4B**).

Consistent with these changes in Self-Responsibility, at the Refresher time point, Tier II teachers significantly increased their ratings on their Goals for Relationships with Students (TM_SG, **Table 3**). After the workshop, Tier II teachers increased their ratings on their Social Support for Students (IQ_IQ, **Table 3**).

To address teachers' ability to provide social and emotional support for students, the following group of scales and subscales contained questions pertinent to some aspect of student support: Self-efficacy and all 3 subscales (TM_TSE), Goals for teacher-student relationships (TM_SG), Self-responsibility for relationships with students (TM_SR subscale) and Social support

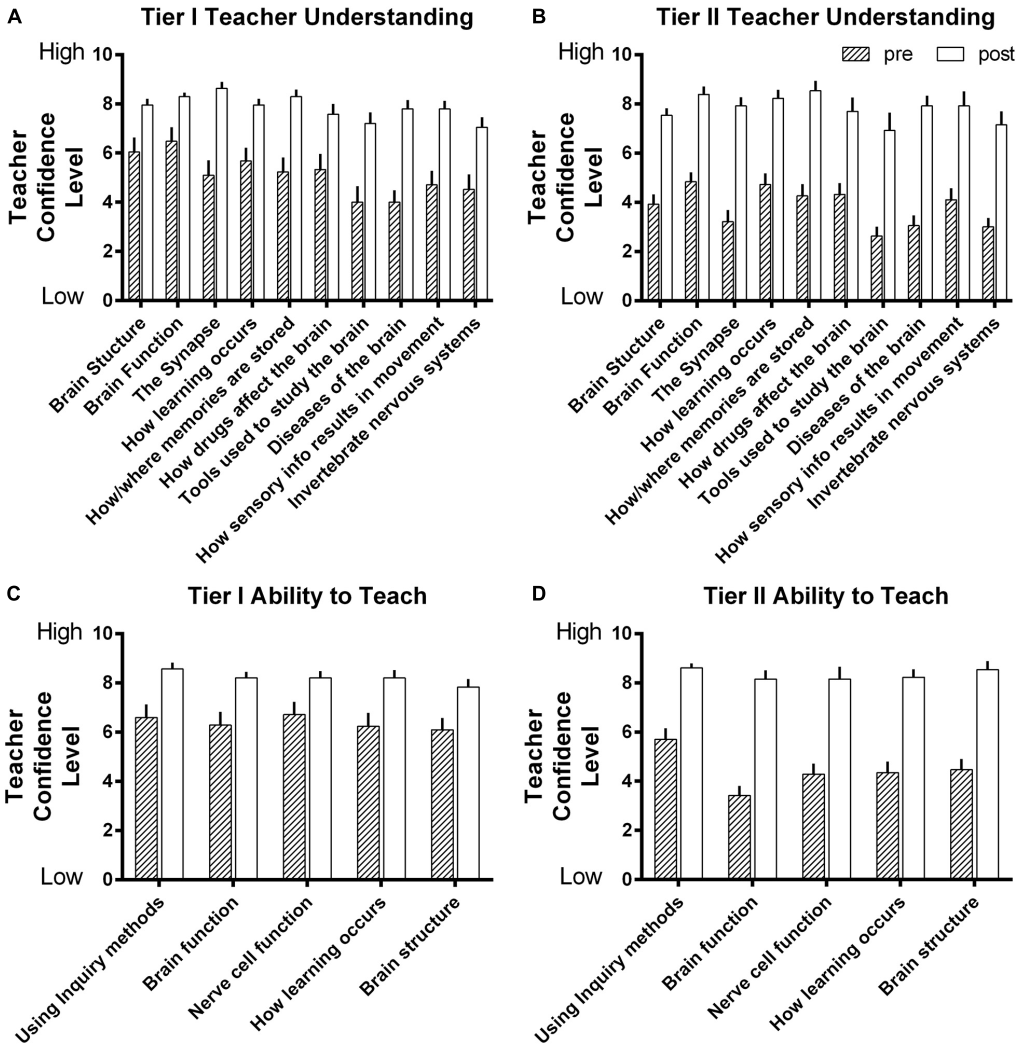

FIGURE 1 | Teachers' self-confidence ratings on their knowledge of neuroscience **(A,B)** and their ability to teach neuroscience **(C,D)**. Both Tier I **(A,C)** and Tier II **(B,D)** teachers significantly increased their self-confidence on all content items (Bonferonni post-tests all $p < 0.05$ or better after two way ANOVAs: **(A)** $p < 0.0001$ pre to post, $p < 0.001$ for item, ns interaction. **(B)** $p < 0.0001$ pre to post, $p < 0.05$ for item, ns interaction. **(C)** $p < 0.0001$ pre to post, ns for item, ns interaction. **(D)** $p < 0.0001$ pre to post, ns for item, ns interaction). Bars are mean + sem; Tier I $N = 21$ pre, 24 post, Tier II $N = 37$ pre, 13 post.

for students (IQ_IQ subscale). Of these seven measures, as a group, Tier I and II teachers each changed significantly on five of them (**Tables 2**, **3**).

At the Refresher time point, Tier II teachers registered significant increases regarding their self-responsibility for student motivation and achievement and for the quality of their teaching (**Table 3**). Tier I, but not Tier II, teachers significantly increased their overall enthusiasm for teaching (**Tables 2**, **3**). Significant increases were registered on the classroom management scale by Tier I teachers and on the Dealing with Disruption scale by Tier II teachers. Tier II teachers significantly improved their overall ratings on the Beliefs scale whereas Tier I teachers' beliefs changed only on the Direct Transmission Beliefs subscale. Tier II, but not Tier I, teachers registered a small gain in their Goals for teacher-student relationships. No changes occurred in either tier on the scales measuring their planned persistence to continue teaching, understanding of assessments, willingness to invest personal time, and the full instructional quality scales (**Tables 2**, **3**).

Teacher Interviews

Qualitative analysis of the Tier II teacher interviews uncovered three major themes, variously related to the affective-motivational scales. First, teachers demonstrated more confidence in their ability to reach all students and motivate them to learn, a theme that aligns with teacher self-efficacy and self-responsibility for student engagement, consistent with their ratings on the TSE and Self-responsibility scales. Second, teachers employed more student-centered pedagogical practices, an instructional strategy. Lastly, teachers increased their own emotional regulation and adapted their behaviors to prevent classroom disruption through

TABLE 2 | OECD Scales included in the Tier I teacher survey.

		Retrospective Pre-training			Post-training				
Designator	**Scale and sub-scale names**	**Mean**	**SD**	**N**	**Mean**	**SD**	**N**	***p***	***d***
TM_TSE	Teacher self-efficacy	59.8	19.0	23	78.6	8.6	24	**<0.0001**	1.28
TM_TSE	Student engagement	18.4	6.2	23	23.4	3.0	24	**0.0008**	1.03
TM_TSE	Instructional strategies	17.0	6.3	23	24.3	2.9	24	**<0.0001**	1.50
TM_TSE	Classroom management	19.5	6.4	23	24.7	3.1	24	**0.0010**	1.04
TM_M	Motivation to teach	59.6	18.8	23	68.5	7.8	24	**0.0382**	0.62
TM_M	Ability	15.6	5.2	23	18.1	2.7	24	**0.0452**	0.60
TM_M	Intrinsic career value	10.7	3.4	23	12.3	2.2	24	0.0544	0.58
TM_M	Extrinsic career value	12.5	5.2	23	12.1	4.7	24	0.8077	−0.07
TM_M	Social career value	20.8	7.2	23	26.0	2.8	24	**0.0054**	0.94
TM_SR	Teacher self-responsibility	52.7	16.4	23	60.0	15.3	24	0.1170	0.47
TM_SR	For student motivation	13.0	4.3	23	13.6	5.4	24	0.6854	0.12
TM_SR	For student achievement	12.4	4.3	23	13.8	4.8	24	0.3112	0.30
TM_SR	For relationships with students	13.0	5.1	23	15.7	4.2	24	**0.0490**	0.59
TM_SR	For quality of teaching	14.3	5.5	23	17.0	4.7	24	0.0755	0.53
TM_SG	Student goals (goals for teacher-student relationships)	18.3	7.4	22	21.8	5.4	24	0.0708	0.55
TM_E	Enthusiasm	10.9	3.6	22	12.8	2.3	24	**0.0359**	0.64
TM_PP	Planned persistence for teaching	10.0	3.6	22	11.7	2.3	23	0.0621	0.57
TM_WT	Willingness to invest personal time	26.1	7.8	22	29.9	5.8	24	0.0641	0.56
IQ_IQ	Instructional quality	31.2	4.2	23	32.7	4.7	24	0.2485	0.34
IQ_IQ	Monitoring	6.4	1.6	23	6.6	1.2	24	0.6427	0.14
IQ_IQ	Cognitive autonomy support for students	12.8	1.9	23	12.7	2.6	24	0.8128	−0.07
IQ_IQ	Social support for students	12.0	3.4	23	13.5	2.6	24	0.0930	0.50
IQ_CM	Classroom management	29.8	5.2	22	32.8	4.2	23	**0.0356**	0.65
IQ_UA	Understanding assessment	16.6	3.0	22	17.6	3.8	23	0.3077	0.31
TALIS 43	Dealing with disruption	12.5	2.6	19	11.4	3.3	14	0.3173	0.36
TALIS 29	Beliefs	34.7	5.7	21	36.7	5.7	24	0.2574	0.34
TALIS 29	Direct transmission beliefs about instruction	12.3	2.4	21	14.1	1.9	24	**0.0065**	0.86
TALIS 29	Constructivist beliefs about instruction	11.2	3.0	21	11.6	2.8	24	0.6923	0.12

Subscales are indented. p-values determined by two tailed t-test comparing pre to post d, Cohen's d, effect size. Statistically significant p values are bolded. Scales were developed for the ITEL-TKS or TALIS programs (Sonmark et al., 2017; OECD 2008). Higher values indicated more agreement or better abilities. The valence of the TALIS 43 scale has been reversed so that larger numbers represent improvement in handling classroom disruptions.

TABLE 3 | OECD Scales included in the Tier II teacher survey.

		(a) Pre-training				(b) Post-training				(c) Refresher					
Designator	**Scale and sub-scale names**	**Mean**	**SD**	**N**	**a–b**	**Mean**	**SD**	**N**	**b–c**	**Mean**	**SD**	**N**	**a–c**	***p***	**η 2**
TM_TSE	Teacher self-efficacy	70.4	10.4	45	*	76.8	13.0	38		73.3	9.4	56		**0.0296**	0.05
TM_TSE	Student engagement	22.0	3.5	45	**	24.3	4.0	38	**	21.6	5.3	56		**0.0121**	0.06
TM_TSE	Instructional strategies	21.1	4.5	45		23.6	4.4	38		21.3	5.8	56		0.0504	0.04
TM_TSE	Classroom management	22.2	4.2	45		23.1	5.3	38		21.3	6.1	56		0.2776	0.02
TM_M	Motivation to teach	72.0	13.5	44		73.6	8.2	38	**	80.0	3.1	56	****	**<0.0001**	0.14
TM_M	Ability	17.8	3.8	44		18.7	3.2	38		20.1	1.0	56	***	**0.0004**	0.11
TM_M	Intrinsic career value	12.3	2.5	44		13.0	1.9	38		13.6	0.8	56	**	**0.0035**	0.08
TM_M	Extrinsic career value	16.0	4.9	44		15.8	4.0	38	****	19.4	1.7	56	****	**<0.0001**	0.18
TM_M	Social career value	25.5	4.4	44		26.1	3.1	38		26.9	1.5	56		0.0788	0.04
TM_SR	Teacher self-responsibility	59.5	15.1	45		65.4	13.1	37		70.7	9.4	56	****	**<0.0001**	0.13
TM_SR	For student motivation	14.1	5.6	45		15.5	4.7	37		17.3	3.2	56	**	**0.0030**	0.08
TM_SR	For student achievement	13.4	5.3	45		15.3	4.4	37		16.8	3.4	56	***	**0.0008**	0.10
TM_SR	For relationships with students	14.2	5.1	45		15.8	5.1	37		17.4	3.2	56	**	**0.0021**	0.09
TM_SR	For quality of teaching	17.7	4.0	45		18.8	3.0	37		19.3	2.3	56	*	**0.0455**	0.04
TM_SG	Student goals (goals for teacher-student relationships)	23.6	6.3	44		25.6	3.8	37		26.0	2.7	56	*	**0.0237**	0.05
TM_E	Enthusiasm	12.4	2.7	43		12.5	3.3	40		13.5	0.9	56		**0.0393**	0.05
TM_PP	Planned persistence for teaching	12.0	2.8	44		12.5	1.7	38		12.9	1.1	56		0.0516	0.04
TM_WT	Willingness to invest personal time	31.0	5.6	46		31.3	6.4	39		32.3	3.0	56		0.3763	0.01
IQ_IQ	Instructional quality	32.1	5.4	41		32.8	3.3	39		34.4	2.8	25		0.0796	0.05
IQ_IQ	Monitoring	6.1	1.5	41		5.8	1.4	39		6.1	1.1	25		0.4555	0.02
IQ_IQ	Cognitive autonomy support for students	12.9	2.9	41		12.5	2.7	39		13.9	1.7	25		0.1192	0.04
IQ_IQ	Social support for students	13.1	3.6	41	*	14.5	1.9	39		14.5	1.7	25		**0.0271**	0.07
IQ_CM	Classroom management	32.8	7.9	45		32.8	7.2	38		35.0	3.9	25		0.3797	0.02
IQ_UA	Understanding assessment	16.7	3.1	44		17.7	3.9	39		18.2	1.9	25		0.1348	0.04
TALIS 43	Dealing with disruption	11.3	2.1	44	**	12.8	2.2	38	****	9.7	1.7	56	***	**<0.0001**	0.30
TALIS 29	Beliefs	34.5	9.0	44		36.6	6.7	38		39.2	4.9	56	**	**0.0041**	0.08
TALIS 29	Direct transmission beliefs about instruction	13.0	3.5	42		12.8	3.0	38		13.4	2.2	57		0.5272	0.01
TALIS 29	Constructivist beliefs about instruction	11.6	2.5	40		11.7	2.4	38		12.6	1.7	57		0.0651	0.04

*p-values determined by one-way ANOVA followed by Tukey's post-hoc comparisons between the designated time points. *, **, ***, **** represent $p < 0.05$, 0.01, 0.001, 0.0001, respectively. Statistically significant p values are bolded. Scales were developed for the ITEL-TKS or TALIS programs (OECD, 2008; Sonmark et al., 2017). Higher values indicated more agreement or better abilities. The valence of the TALIS 43 scale has been reversed so that larger numbers represent improvement in handling classroom disruptions.*

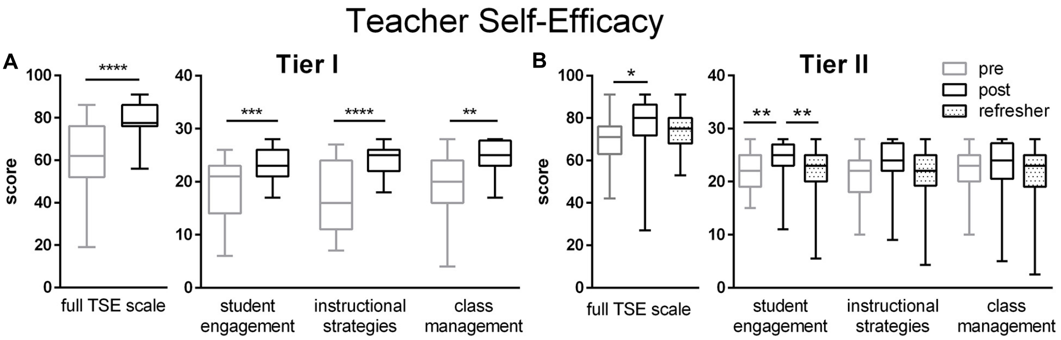

FIGURE 2 | Teacher Self-Efficacy ratings for Tier I **(A)** and Tier II **(B)** teachers on both full TSE scales and subscales for Student Engagement, Instructional Strategies, and Class Management. Gains in TSE were made during the workshop for both Tier I and Tier II teachers (**Tables 2**, **3**). Pre (gray) represent retrospective pre ratings for the Tier I teachers and pre-workshop ratings for the Tier II teachers. Boxes represent 25th to 75th percentiles with an internal bar at the median. Whiskers delineate maximum and minimum data points. Tier I $N = 23$ pre, 24 post; Tier II $N = 45$ pre, 38 post, 56 refresher.*, **, ***, and **** represent $p < 0.05$, 0.01, 0.0001, and 0.00001, respectively.

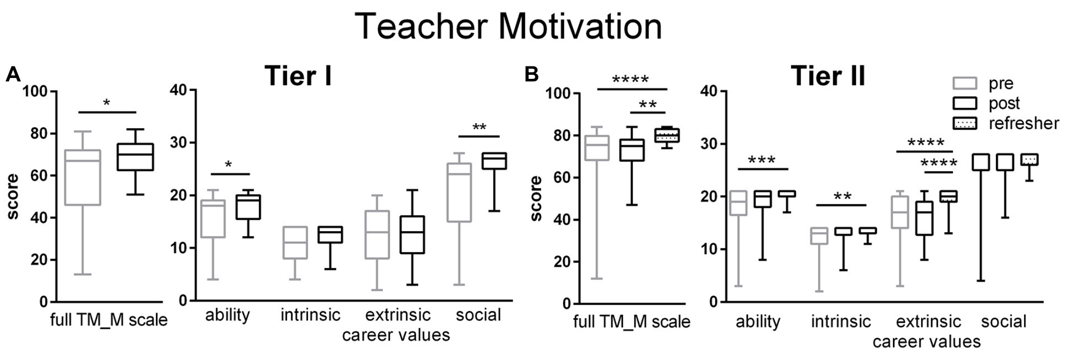

FIGURE 3 | Teachers Motivation to Teach ratings for Tier I **(A)** and Tier II **(B)** teachers on both full TM_M scales and subscales for Teaching Ability, Intrinsic Career Values, Extrinsic Career Values and Social Career Values. Gains in Teacher Motivation were made more for Tier II than Tier I teachers (**Tables 2**, **3**). Pre (gray) represent retrospective pre ratings for the Tier I teachers and pre-workshop ratings for the Tier II teachers. Boxes represent 25th to 75th percentiles with an internal bar at the median. Whiskers delineate maximum and minimum data points. Tier I $N = 23$ pre, 23 post; Tier II $N = 44$ pre, 38 post, 56 refresher.*, **, ***, and **** represent $p < 0.05$, 0.01, 0.0001, and 0.00001, respectively.

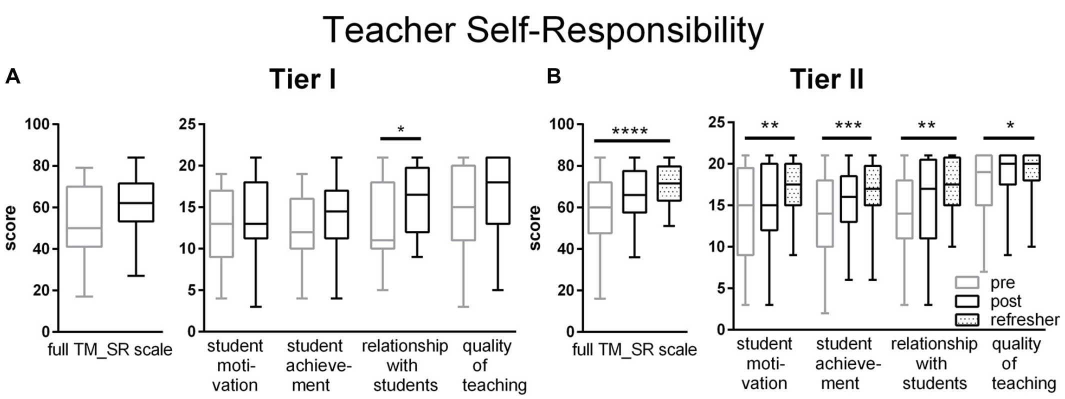

FIGURE 4 | Teachers Self-Responsibility for Teaching ratings for Tier I **(A)** and Tier II **(B)** teachers on both full TM_SR scales and subscales for student motivation, student achievement, relationships with students and quality of teaching. Gains in Teacher Self-Responsibility were principally made for Tier II teachers at the Refresher time point (**Tables 2**, **3**). Pre (gray) represent retrospective pre ratings for the Tier I teachers and pre-workshop ratings for the Tier II teachers. Boxes represent 25th to 75th percentiles with an internal bar at the median. Whiskers delineate maximum and minimum data points. Tier I $N = 22$ pre, 24 post, Tier II $N = 41$–44 pre, 38 post, 56 refresher. For the post tests, *, **, ***, and **** represent $p < 0.05$, 0.01, 0.001, and 0.0001, respectively.

engaging all learners, a theme aligned with TSE in the realm of classroom management.

Teacher Self-Efficacy and Self-Responsibility

TSE encompasses teachers' beliefs that they can effectively engage students to learn using appropriate instructional strategies and classroom management (Tschannen-Moran and Hoy, 2001). All teachers commented upon their broadened pedagogical skills, indicating more competence and greater self-efficacy beliefs. This change in TSE was evident from their embrace of more participatory pedagogy and their decreased use of punitive discipline, as described below. Teachers felt they now had the skills to address the needs of all students, through allowing students to ask questions, discuss, and interact and through giving responsibility for learning to the student (**Table 4**). The definitiveness of these statements attests to the way they have internalized the instructional strategies modeled during the workshops and have incorporated them into their own practices. Teachers' statements revealed they were able to predict student reactions when they employed these new techniques. Beyond recounting their newly adopted instructional strategies, they also commented upon their successes in student engagement and classroom management. Teachers described engaging students in the lesson through including their voice and participation in the topic to be taught; "Because by breaking them into the class discussion, you will feel a part and everybody got their own strength."

The training led to teachers taking time to analyze, reflect upon, and articulate their own roles in the classroom. The change in roles was clearly described by one teacher: "now, I feel that I have a responsibility to identify each and every one of my student[s'] needs and help them to meet the needs, so the student [is] benefiting. In the classroom, I'm not teaching student[s] to be afraid of me any longer, I'm helping them to learn. I'm facilitating their learning process, so instead of writing plenty on the board, I give activities." In addition, teachers talked about encouraging students and building up the student's own relationship to education and learning. "I always tell them that we the teachers, we are like people who are just there to show you the way. We are there to show you where you should go. Because the time allotted to us is not enough in class to make you understand everything. So we show you the way and I encourage my students to do further research, to go beyond what I'm giving them. So that they will better understand the subject matter."

Teachers felt they now understood the learning process and took responsibility for the engagement and tenor of the class. Teachers attested that the new teaching skills they acquired (**Table 4**) engaged and motivated students to attend to class material; "we should make a student to grow up with the lesson, to invite them . . . to be connected with the lesson." Teaching became an interactive process involving both students and teachers: "Instead of talking lots in class... I'm using [an] interactive method, like both students and teacher, both of us will do work together." Capturing students' attention and keeping them engaged avoided leaving space for annoying or disruptive behaviors to take hold.

Teachers moved from ignoring their relationships with students to focusing upon building those relationships as a means to promote learning and decrease behavioral issues in the class. An important part of building those relationships was crediting students for their contributions and participation: "I have also learned to give student credit as to what can be their input." Teachers identified students with comprehension problems to further help those students to acquire the knowledge: "I had a student who was very difficult to talk to. . . . He never used to be so active. When I started showing that relationship . . . to him, he started pulling himself [up in class]." Teachers reached out to students to address problems while balancing the issues of equity, motivation, achievement and inclusiveness in the classroom. Beyond the classroom, teachers also strove to build relationships to help students solve personal problems that hindered student learning: "And hook yourself to the student and draw them to you by . . . interaction with them, . . .Then they too, their mind will be relaxed on your lesson or be able to grab what they will need, for your lesson." Teachers also shared relationship-building experiences with the whole class like eating together, sharing fun, and using engaging openers. Central to the idea of many of these comments is that teacher behavior toward students can either benefit the learning or detract from it. As one teacher expressed, "For when I left [the workshop] and I went back, I had a real mindset; helping me to reach out to relate to them, when to keep quiet. How to, you know, raise my voice and even how to even . . . be patient with them."

Teachers saw that the adolescent and child brain are different than adult brains, and that development of students' brains could be influenced by teachers and education. They learned to recognize students with social, emotional, behavioral and MH problems and to engage students in addressing these problems. As one teacher recounted, "through this training. . ., I have noticed that as a teacher you have to observe the class and know that there are students who have mental health problems." These educators learned to manage student misbehavior as a part of either the students' development or their social lives outside of class. In short, teachers saw themselves as more resilient and saw students as well-rounded people with their own lives. Overall, teachers attributed their changes to understanding how the brain works: "But I think the issue of this training has brought to a fairer concept what are some of the things that we need to do in order to build a brain up and what are some of the things that are prohibited not to do with the brain."

Instructional Strategies

The interviewed teachers had shifted their approach from a teacher-centered lecture or presentation to a student-centered active learning focus (**Table 4**). Teachers engaged students across the class intellectual and social hierarchy though use of group work, pitching the content to a level where everyone could understand, and providing additional content as needed. They included students with social, emotional, behavioral or MH problems, who previously might have been ignored or punished. Teachers paced their teaching to include everyone, not just the top students. "Mainly, my focus is to always to get at those that are not really active. Because by bringing them into the class

TABLE 4 | Pedagogical skills acquired during the trainings.

# of comments	Pedagogical skill mentioned	Example quote
19	Differentiating lessons for different level learners	"... for the fast learner, after presenting ... I have to give extra curriculum. ... for the normal learner ..., I help them because they are already in reach, ... for the slow learner, what I do, I spend much time with them, ... I create extra time to go over the lesson."
15	Putting students in groups, promoting peer learning	"I put them in group, like in one group you'll find the fast, the normal, and the slow [learners]. In time, ... every one of them starts working together." "Maybe they will better get what they never get from me, they will be able to learn it from their colleague. So, I tell the fast learners to help the slow learners in their lesson."
12	Class interactions and discussions	"... now my class, like ... you saw this morning, is participatory" "I gave student the opportunity for them to give their view and add theirs relating to a particular topic. That makes the class very interactive."
7	Using hands-on activities	"I try to create activities that will engage each and every student. For example, instead of just going on a board or teach, I learn that I should give hands-on activity."
7	Assessing formatively from student explanations	"So I create challenging activity ... that will require evaluation in sentences and all of them will be in a path [to learning]. At the end of the day, the objective will be met."
5	Engaging openers	"I have little drama before we went through our topic and (with) that I can get everybody attention in the class."
4	Encouraging student input	"... each person would have the pen, writing something, contributing toward the question. And then after everyone will come together and give their contributions."
4	Questioning and risk taking	"I give students the opportunity to ask questions or I ask them question as to what have they learned, what do they want to learn, and what do they know as well?" "you have to encourage students to ask questions and when they would ask those questions you would be able to explain to them better."
3	Expanding wait time	"... whenever we ask a quiz question, we should give students a breathing space for them to reflect or think about the answer. Before then, I never used to do that. I just posed my question and... I want answer right away."
3	Gently correcting but not punishing after mistakes	"Even if he or she says the wrong thing, I will also encourage them because they have made some effort."
3	Explaining content multiple ways	"... some of them learn by touching, by seeing, by their actions."
1	Reflection	"I also learn to give student the opportunity to reflect their mind on past event or past topic."
1	Asking open-ended rather than yes/no questions	"... you should ask the questions that require explanation"
1	Using analogies and making content relevant to students' lives	"I try to take my classroom discussion to our everyday real life stuff."
1	Giving students breaks	"I never used to allow my students to just walk out of the class [to go to the bathroom], but now I give students the chance to walk out, come back in."

discussion, you will feel a part and everybody got their own strength(s). Once you focusing on... the person who is always answering, you are not . . . doing justice to the other people." Teachers valued contributions from the whole class, rather than seeing inactive and underachieving students as nuisances; "You make sure in the class that the slow learner will also understand the topic for that particular day. . . . you just stick with it, make sure that everybody in the class understands it before you move on. . ." Teachers seem to recognize that bringing their presentations to the level of the "slow" learner results in more learning for the whole class.

Teachers implemented peer-to-peer learning through discussions and having students work in mixed level groups (**Table 4**). Teachers designed lessons to focus on big ideas, relevant to students' lives, illustrated through hands-on activities. They mentioned using group work and how it helped students to learn from each other in a new way. Skills required for group work and discussions needed to be learned and teachers seemed to appreciate this. According to one teacher, "In time, ... every one of them starts working together." Implementing group work made the lessons interactive and participatory. In the words of one teacher, "It's good to put them in groups and get some diverse views. Then students learn from students." The constant reference to "mixing slow and faster learners" as a post-training practice may indicate that teaching to the top students and leaving some of the class behind is a common practice. These teachers no longer considered themselves the only source of knowledge in class, but saw learning as a product of all involved: "We as teachers, we are giving them [students] these groups, we ourselves, we are learning from them, too."

Teachers recognized they had grown in their overall understanding of learning as a biological function of the brain that requires time and practice on the part of the learner, and frequently referenced time among the challenges to implementing these changes. They allowed students time to reflect before answering a question: "Like, whenever you are teaching, you are supposed to be allotting time to students when they ask their question. You give them time, let them have relax, to respond to you." Most importantly, teachers were cognizant that students needed time to process new information, question it and share it among peers. Changing their practice took more time to adapt the lesson for different learning abilities ("slow" and "fast"). Teachers took time after class for students and put time into those relationships. Teachers reported monitoring students over time for changes in mood or behavior as indicators that they were encountering MH problems or social issues. They acknowledged that the process of change is iterative and requires time, analysis and attention: "Because in order to analyze what I have been taught to be applied in the classroom comparing it with the old one, I need to critically analyze as to what I'm supposed to do in order to get things going well. So, these are challenges I have been faced with."

Additional challenges included getting colleagues and students accustomed to the new teaching approaches. Abandoning the way that you were taught, as a teacher, also requires a huge leap of faith. As one teacher recounted, "Another challenge could be for the student to understand the new method I'm applying in the classroom. Sometime, a few will look at me [when I] . . . say, "Pupils, please sit in group." When I tell the children, they say, "[teacher] you coming put us in our group again oo.". . . So for them to agree with the change, sometime, it can be challenging. But at the end of the entire exercise, they can be happy and many of the time, they can call for more and more of the activities, so I can say even though, it's a challenge, but it's a pleasure to do it." Teachers expressed concern over getting colleagues to share their new views of teaching and learning; as one teacher said, "I'm struggling with it because I want to impart that knowledge that the neuroscience training facilitators has given me. I've struggled with it because I want to impart that knowledge onto all of us." When discussing these challenges, teachers demonstrated a willingness to pursue growth and change. As one teacher said, "when somebody takes step forward there will be challenges, but the ability to overcome those challenges is what matters." Despite these difficulties, teachers viewed their changes as helpful, saying, "Even though it is challenging but I'm working [on it] . . . the training has made me to know those positive changes as a teacher." Teachers also expressed concern over the lack of basics such as classroom books, resources, lab materials and even back pay, issues this training could not address.

Teacher Self-Regulation

Teachers recognized that their own approaches to managing their classrooms had changed. Teachers mentally connected the long term consequences of emotional and physical trauma to student learning outcomes and consequently they controlled their own behaviors to decrease any negative impact they might have on students. "As an instructor in a class sometimes a student annoys you, you get angry, you call the student up what? and slap the student's head, which is very wrong. The workshop, the training has made us to understand that such things is wrong and believe me I decided not to practice that both home and in my school that I teach." Teachers self-reported curtailing use of harsh disciplinary practices (Brick et al., 2021).

Teachers evolved from being aloof, vexed or openly angry at aberrant student behaviors to becoming encouraging, patient and developing good working relationships. "In the workshop, . . .prior to that, . . . anything a student does in class . . .I want to react. . . . My way of punishing them when even they are in the wrong direction [misbehaving] when I'm teaching, [now] I know the way I [will] approach them. Before then, I used to be the type of teacher who, 5 min [euphemism for "had no patience for that"], even though I was not the type to beat on students." They described learning to control reactions, either by stopping negative reactions (profanity, temper) or by engaging positively. "I was the kind of teacher...I was very much temperamental and very restrictive, frightening students. Well, since I came to this workshop, this training, my temper dropped a little bit." Teachers acknowledged their former role in promoting a negative classroom culture and in that acceptance gained power to now manage the classroom better. "When I went for the training, I noticed that even if [the class is] disturbing, you have a method that you would do at least to quiet the class and then you go ahead with your teaching." All teachers emphasized the need to talk directly with students with non-compliant classroom behaviors to determine the circumstances underlying these behaviors. They preferred to talk to students one-on-one or build trust through kindness or generosity. These conversations did not occur when the student was "hot" or angry. "Firstly, if the person is behaving rude, you try to cool them down. You will not do it in the class [by saying] "shut up, stop disturbing," no. After class, you call the student by your side, or sometimes you just giving them lunch... You will be able to cool them down and you help them calm down, at least you help them solve their mental health problems." Thus teachers employed self-restraint and strategies to better manage the class.

DISCUSSION

This study examined how knowledge of the neuroscience of learning, memory, stress and emotions altered Liberian secondary science teachers affective-motivational attitudes toward their practice. Several aspects of the program were novel. This represents the first implementation of such a training program in a LMIC using a tiered training-of-trainers model. In addition, this study is the first application of an internationally constructed instrument to measure the motivational aspects of teacher competence following PD (Sonmark et al., 2017). As expected, the training-of-trainers model adapted the Tier I information to local training needs while both preserving important content and pedagogical practices and adding content on local social, emotional, behavioral and MH issues. A wide variety of teacher attitudes were observed to change either immediately or with time and practice after attending the PD. As predicted, TSE improved among both tiers of participants. Attitudes were more positive about teachers' ability to structure lessons, engage and manage students in the process of learning. Both Tier I and Tier II teachers gained confidence in their understanding of neuroscience and ability to teach it. Surprisingly, after the workshop at the Refreshers, teachers' motivation to teach, self-responsibility and enthusiasm had increased. In interviews, Tier II teachers commented on their new ability to reach all students and motivate them to learn, to utilize more student-centered pedagogies, and to self-regulate their own emotions to promote better classroom management, themes that align with TSE. These narrative changes represent development of their professional identities as teachers, encouraging student behaviors that promote learning, such as asking and answering questions or learning from their peers, instead of encouraging behaviors that simply lead to passing.

For both tiers, the gains in teacher knowledge, confidence in that knowledge and confidence in their ability to teach neuroscience were comparable to previously reported gains from similar workshops in a high income country (see Figures 4, 5 in MacNabb et al., 2006b). In the current setting, the Tier II teachers were instructed by their Liberian peers, the Tier I Leadership Team. This demonstrates that neuroscience knowledge can be effectively transmitted in a training-of-trainers format. Neuroscience is often considered hard, producing anxiety on the part of learners (Birkett and Shelton, 2011). However, when the neuroscience content is narrowed to concepts pertinent to learning and memory and taught using lessons designed for secondary schools, it becomes accessible to all learners (Dubinsky et al., 2019). The Tier II teacher acquisition of confidence in this knowledge demonstrated that despite expected losses of some content from shortening the workshop, teachers felt they could successfully convey the neuroscience relevant to teaching to their peers. Indeed, the adaptation of workshop content to the Liberian educational context may have accounted for the Tier II, but not Tier I, improvements on survey items related to dealing with disruption, teacher self-responsibility, student achievement and student relationships.

Teacher Self Efficacy

TSE refers to teachers' beliefs regarding their ability to produce student learning, i.e., the personal ability to provide appropriate and meaningful instruction and the outcome ability to achieve appropriate student growth and performance (Bandura, 1997). Personal self-efficacy included teachers' self confidence that they have mastered the subject matter sufficiently and had the confidence to teach it appropriately to student audiences (Bandura, 1997). The instrument operationalizing assessment of TSE recognizes that resources and environments constrain practices and focuses upon activities normally encountered in teachers' work: student engagement, instructional strategies, and classroom management (Tschannen-Moran and Hoy, 2001; Sonmark et al., 2017). In a review summarizing 40 years of TSE research, TSE has been positively linked to measures of teachers own well-being, personal accomplishment, job satisfaction, and commitment (Zee and Koomen, 2016). TSE also positively influences many aspects of teachers' practices, including employing effective and innovative learning strategies, connecting to students' lives, providing social and emotional support for students, classroom management, differentiation, and inclusivity (Zee and Koomen, 2016). Overall, high TSE is associated separately with greater use of constructivist, student-centered instructional approaches, and better academic achievement (Zee and Koomen, 2016). Across national boundaries and collectivist vs. individualist cultures, teachers with higher self-efficacy reported more productive teaching practices and higher job satisfaction (Klassen and Chiu, 2010; Vieluf et al., 2013). PD frequently leads to increased TSE (Zee and Koomen, 2016), as also demonstrated here. Similarly, PD in inquiry science teaching involving active participation by teachers, reflection, and follow-up increased their self-efficacy for specifically teaching scientific inquiry (Lotter et al., 2018). Here, teachers' confidence in their neuroscience knowledge reflected their "cognitive mastery" of that knowledge, a critical part of self-efficacy (Palmer, 2006). Liberian teachers' new ability to engage students, use student-centered practices and manage their classrooms more effectively were a major departure from their previous beliefs and practices, as revealed in the surveys and interviews, and constitute improvements in their TSE.

At follow-up, the relaxation of TSE attitudes to initial levels attests to the difficulty of sustaining new beliefs and practices in the absence of adequate support. A similar reversal at follow-up of end of workshop gains in self-efficacy for inquiry teaching were reported in a pilot study of US middle school science teachers (Lotter et al., 2016). When the samples size was increased, a sustained increase in self-efficacy for inquiry teaching was observed, indicating that weak elements of a pilot intervention can be subsequently corrected (Lotter et al., 2018). Alternatively, by the time teachers had been implementing new classroom practices for several months, they may have reset their internal assessment of their own capabilities. Future studies should administer a retrospective pre-survey at the same time as the follow-up survey, so that both reflect teacher's internal ratings on the same day. Retrospective pre-tests can be more accurate assessments of prior knowledge since one doesn't realize the extent of initial ignorance until after learning the new material (Levinson et al., 1990; Bhanji et al., 2012). In addition, more, continuous follow-up support may be needed to solidify the initial TSE gains.

Interviewee comments on instructional practices clearly favored a more student-centered approach. Without observing participants in their classrooms, interpretations of the Beliefs scale become difficult. Tier I ratings of statements associated with direct instruction increased while Tier II ratings trended toward increasing constructivist beliefs. The individual questions on this scale that showed change were "Effective/good teachers demonstrate the correct way to solve a problem" and "Instruction should be built around problems with clear, correct answers, and around ideas that most students can grasp quickly,"(OECD, 2008). Even in a constructivist-oriented classroom, having a teacher summarize by providing a correct interpretation or solution, is an excellent practice. Similarly, initially focusing students on doable problems so that they succeed and gain confidence provides scaffolding necessary for subsequent deeper or open-ended challenges. In the absence of direct assessment of these teachers' pedagogical practices before and after the workshop, these survey results should be interpreted with caution.

The qualitative impacts of the training on teacher's emotional regulation and classroom management were unexpected, as these aspects of teaching had not been intentionally targeted in the trainings. Altering teachers' views of student behavior and potential to learn may have provided them with the patience to approach behavioral problems from a more tolerant and less stressful perspective. Unexpected impacts upon classroom management have previously been reported from interventions targeting lowering teacher stress through mindfulness and social-emotional skills trainings (Jennings et al., 2017). Changing classroom management strategies reflects a major shift in participants' thinking. Culturally, maintaining classroom discipline is highly valued by Liberians, being the second strongest reason parents cite for choosing a school, after teacher quality (Longfield and Tooley, 2017). In the interviews, teachers indicated they maintained better control of their own emotions when responding to student misbehaviors, a form of self-regulation which is also linked to professional competence (Klusmann et al., 2008; Kunter et al., 2013). Self-regulation was not directly assessed in the extensive ITEL-TKS instrument. While the interviews indicated management strategies shifted toward promoting student engagement, the survey results did not uniformly reflect such changes. The absence of change in the Tier II classroom management ratings may represent the fact that teachers who employ student-centered practices often do not have as much control over classroom behaviours (Owens and Tanner, 2017). Consistent with interviewee's reports of allowing more discussion and group work, Tier II ratings decreased on the Dealing with Disruptions scale. Questions on this scale address noise levels, classroom interruptions and getting students to quiet down, behaviors that would be expected to increase with more student-centered practices (Owens and Tanner, 2017). The Liberian teacher testaments to using both group work and a more positive classroom climate parallel recommendations for effective pedagogy in LMIC (Westbrook et al., 2013).

Gains in the Liberian teachers' skills for self-awareness, emotional regulation, and building teacher-student relationships parallel three of the five competencies recognized for effective social and emotional learning (Schonert-Reichl et al., 2017). For adults and children, SEL concerns the processes for developing social and emotional competencies for self-awareness, social awareness, responsible decision making, self-management and relationship management (Schonert-Reichl et al., 2017). To promote better student learning of social-emotional skills, teachers must be supported in developing their own social-emotional competencies (Jones and Kahn, 2017). Teachers with better social-emotional skills engage more with their students, build stronger positive relationships and engage in better classroom management (Jones and Kahn, 2017). Teachers in comprehensive skill building programs learned how to recognize, understand and regulate their own emotions and demonstrated more positive teacher-student interactions, responses to emotions and caring beyond the classroom (Brackett et al., 2019). Providing the neuroscientific basis for how emotions and stress influence learning and memory in conjunction with discussions of effective teaching and how to recognize student emotional issues in the Liberian program appeared to produce comparable results. While the pillars of social-emotional competency programs (Osher et al., 2016) were not specifically taught here, combining those principles with a neuroscientific foundation for learning and memory may enhance effectiveness of future programs.

Motivations for Teaching

The improvements in motivations for teaching for both tiers of teachers was not expected. Teachers' motivation for teaching includes their own professional goals, sense of responsibility, and enthusiasm as well as their psychological needs. Most importantly, teacher motivation is related to their pedagogical knowledge and to their decisions to choose and implement high-quality pedagogy (Konig and Rothland, 2012). Teachers' motivation and goals predict their professional learning and subsequent practice (Thoonen et al., 2011; Nitsche et al., 2013). While teacher motivation can positively influence participation in PD (Lauermann et al., 2017) and subsequent implementation of that PD content (Gaines et al., 2019; Osman and Warner, 2020), whether PD can alter teacher motivation has not been widely addressed (Saunders, 2013). Pre-service teachers' initial motivations for teaching are positively associated with their practices at induction (Richardson and Watt, 2014). Changes in pre-service teachers' motivations to teach over the course of their training and induction have been documented. Improvements in teacher motivation can occur when they gain or exercise agency over some aspect of their practice or take on leadership roles (Han and Hongbiao, 2016). Frustrations associated with acquisition of new knowledge can also be demotivating (Han and Hongbiao, 2016) so predictions regarding the impact of PD on teacher motivation are hard to ascertain. The current study suggests that motivations to teach are malleable, even among seasoned teachers, when PD provided new conceptualizations of how learning occurs combined with introductions to constructivist practices.

Teachers' personal and situationally driven motivations may vary according to the larger social or school specific contexts. In an international comparison of the development of mathematics teacher knowledge, an intrinsic interest in math increased motivation to invest time and energy and overcome difficulties, whereas an extrinsic goal to achieve job security decreased that motivation (Blomeke and Delaney, 2012). Among pre-service teachers in the US, intrinsic and social motivations mediate teacher self-responsibility, TSE, interest in PD, personal time investment, and commitment to teaching as a career (Lauermann et al., 2017). In the Liberian context, Tier II teachers registered increases in the motivational subscales of intrinsic, extrinsic and ability values. Tier I teachers registered increases in the subscales of ability and social career values. Neither tier reported changes in willingness to invest personal time. If replicable, the reasons behind these context-specific changes require further investigation.

Liberian teachers demonstrated their persistently high motivation and sense of personal responsibility to improve educational outcomes, despite the economic and structural adversities encountered in their country. Teachers' pay was delayed or not received in the interval between the workshop and the Refresher sessions, a common occurrence and factor that works against professional commitments (Adebayo, 2019; Johnson, 2019; Romero and Sandefur, 2019), resulting in strikes and student protests (Dunbar, 2019). Despite this issue and other structural problems, teacher motivation to teach and self-responsibility for student outcomes increased between the workshop and the Refreshers. These results are in contrast to reported de-motivating outcomes for PD in Malawi where similar structural problems of low or absent pay and empty government promises undermined change (Selemani-Meke, 2013).

Self-Responsibility

Teacher self-responsibility represents what they feel they should be doing in contrast to what they feel they can do (TSE) (Lauermann and Karabenick, 2013). While correlations exist between responsibility and efficacy for each of the subscale factors (student motivation, student achievement, relationships with student, and teaching), the self-responsibility scales capture distinct dimensions of affective-motivational attitudes (Lauermann and Karabenick, 2013). Self-responsibility predicts TSE and interest in PD (Lauermann, 2017). Self-responsibility has generally been examined among teachers at a single timepoint (Lauermann, 2017). Like motivation, how self-responsibility may change following PD has not been previously reported. The change registered in Liberian teachers' sense of self-responsibility was toward forming more supportive relationships with learners. Tier II teachers sense of responsibility for quality of teaching, student motivation and student achievement also increased at the follow-up time point. Following the current training, participants embraced the modeled pedagogies as a means for engaging students and providing social and emotional support. Among high school teachers, embracing a growth mindset view of their students predicts teacher self-responsibility and both predict adoption of mastery practices (Matteucci et al., 2017). Student performance improves following relatively short instruction in the neuroscience of learning and memory linked to ideas promoting a growth mindset (Blackwell et al., 2007; Yeager et al., 2019). Thus, it is plausible that teachers' views of their students' potential also shifted following more intensive neuroscience PD. In addition to teachers' expected roles as content expert, deliverer of quality teaching and role model, Liberian teachers view their positions as also encompassing parenting and counselling (Adebayo, 2019). The changes reported here suggest a deepened commitment of the teachers toward these altruistic goals and a better understanding of how to achieve them as a consequence of their deeper knowledge of students gained during the workshops. The conjoint positive changes in TSE and self-responsibility exemplify theoretical predictions stating that optimistic personal expectations together with opportunities for personal growth should foster more responsibility, even in the face of adverse outcomes (Lauermann and Karabenick, 2011).

Impact of Neuroscience

Neuroscience provided two messages that the teachers embraced. Understanding synaptic plasticity provided a new view of the ability of all students to learn. This idea motivated teachers to adopt more student-centered practices despite large class sizes, limited space and little on-the-ground support. Gaining insight into normal brain growth, development, learning and the neurophysiology of social, emotional and behavioral disorders motivated teachers to change their own behaviors. Their own motivations to increase student engagement became stronger and they applied novel teaching strategies not yet widely practiced in West Africa (Westbrook et al., 2013).

Another strong realization among the interviewed teachers was that the stress felt by students on the receiving end of negative reinforcement was a neurophysiological detriment to their being able to learn. Teachers understood that the presence of stress hormones inhibited brain circuits for learning. Recognizing that producing such stress through shaming or punishment was antithetical to their goals for student learning, teachers opted to improve their self-control. This was an unexpected, but welcome outcome that programs in other countries with such problems may want to replicate (Antonowicz, 2010). Both outcomes demonstrated ways that the neuroscience content provided knowledge of students that teachers utilized in their daily interactions. Their ability to apply this knowledge was facilitated by the content added in Tier II addressing how to recognize student social, emotional and behavioral issues.

Moreover, the training process, content and subsequent changes in practice improved TSE, motivation and self-responsibility for student relationships and success, all aspects of the affective-motivational dimension of teacher competence.

The Liberian neuroscience training demonstrated how understanding basic neuroscience concepts in combination with discussions of students' social, emotional and MH needs may change teachers' affective-motivational attitudes toward students and their practice. For pre-service teachers, the productive friction that occurs when views are challenged acts as a factor driving motivational change (Nolen et al., 2014). Understanding the neuroscience of learning, memory, emotions and stress may have produced such productive friction in the Liberian teachers. Returning to Shulman's conception, the knowledge base for teaching is not fixed or final but should grow with insights from research (Shulman and Shulman, 2004). The development of a detailed neuroscientific understanding of the biological basis for learning and memory within the past 50 years is now ripe for inclusion into teacher training. The Science of Learning incorporates neuroscience into education, reflecting this dynamic view of teacher knowledge (Meltzoff et al., 2009; Ansari et al., 2017; Revai and Guerriero, 2017). Teachers should be able to reflect, incorporate new understandings, and learn from research as well as experience (Shulman and Shulman, 2004). That is what happened in the Liberian program. Challenging teachers to apply this new knowledge of students stimulated them to change their approach toward interacting with students, working to build relationships, motivating and engaging all learners.

Structural Elements That Made the Program a Success

Core components that contributed to the success of the program included the local adaptation of the content, focus on current science teachers, and a Leadership Team that was tasked with executing the model. Rather than impose a top-down training, the Tier II workshops were geared to the local contexts, a practice recommended over policies derived from different contexts (Pritchett and Sandefur, 2013). The local adaptation of the original content and schedule was critical. Going through the process of identifying the important big ideas focused the Leadership Team. Staff helped the Leadership Team remain on task. Additionally, dividing up the neuroscience content among Leadership Team members also lowered the initial barrier to teach this content. Being part of a team strengthened individuals' confidence to be able to share this knowledge with the Tier II audiences. The Leadership Team was motivated by the honor of being included and by their own certainty that the content was important to share with their colleagues.

While implementation fidelity has been an aspirational goal in scaling up programs, a balance must be achieved for accommodating adaptation to the local conditions, as described here (Perez et al., 2016). Among LMIC educational reforms, matching pedagogy to local students' levels and needs provides a cost-effective means of improving learning outcomes, especially when programs are tailored to local conditions (Kremer et al., 2013). Recognizing the adaptive nature of the training-of-trainers process, this study focused primarily on the Tier II teacher outcomes. Tier I teacher outcomes are reported to demonstrate that those teachers who became part of the Leadership Team did indeed learn and understand the delivered Tier I content and were therefore capable of transmitting that knowledge to the Tier II teachers. One benefit of a training-of-trainers structure for teacher PD is the empowerment of Liberian teachers to propagate the change messages. Their agency built local leadership as well as modeled problem solving behaviors for other teachers. Moreover, the local control worked to diminish the perceived power of external funders over the minimal capacity of local institutions (Open Society Foundations, 2015).

Policy Implications

A meta-analysis of the cost effectiveness of various interventions on improving education in LMIC found that providing more effective pedagogy increased test scores more than simply lowering class sizes (Kremer et al., 2013). Combining neuroscience and MH training for Liberian teachers using this training-of-trainers PD model, providing knowledge of how students learn, would therefore be an effective strategy for improving students' educational experiences. The next step in this process would be to formalize current agreements with local teacher training institutions and the Ministry of Education to include neuroscience and social, emotional, behavioral and MH issues in their pre-service and in-service curriculum for teachers. With more universally trained teachers, the neuroscience knowledge of how learning occurs could be transferred to students, where a growth mindset might be promoted (Yeager et al., 2019). Additional benefits that might be expected (and could be studied) would be increasing student motivations to complete their schooling, performance on exit exams, and/or interest in science.

Limitations

All of the data presented here, both surveys and interviews, are teacher self-reports. The limited resources for this pilot program did not permit active observation of classrooms. A number of scales from the ITEL-TKS and the previous TALIS program (OECD, 2008; Sonmark et al., 2017) captured instructional choices, beliefs, management and assessment methods. With the large number of statistical comparisons, two or three significant changes would be expected by chance alone. These self-reports could reflect an incremental change in practice or a report of an intention to change. Since the interviewees were all volunteers, the oral reports may have captured opinions from only the most ardent proponents of change. Future in depth studies should include classroom observations to verify and provide support for enacting changes in teacher practices.

Many of the attitude changes reported for Tier II teachers did not occur until the Refresher time point. Attitudinal changes registered at the end of a 1 or 2 weeks training would not be considered to have withstood the test of time. However, for changes to be registered at the Refresher time point, after teachers had had time to implement ideas encountered in the training, testifies to the lasting effects that can accrue from short interventions.

Since the program intertwined neuroscience and MH content with discussions and modeling of best pedagogical practices, outcomes cannot be attributed to the neuroscience alone. Indeed, PD combining content knowledge with pedagogy produces better student and teacher outcomes than PD focused on content alone (Roth et al., 2019). On an international scale, other PD programs have similarly reported pedagogical improvements, with more enjoyment of school, more acceptance of student-centered pedagogy, and more positive attitudes toward regular students but not those with perceived disabilities (Westbrook et al., 2013). Future programs should consider including an active control group receiving pedagogical training for comparison.

CONCLUSION

The Liberian PD provided teachers with knowledge of the neuroscience of learning, memory, stress and emotions using student-centered pedagogy combined with training on recognizing students' social, emotional, behavioral and MH issues. In experiencing the workshop content as students would, teachers were able to see themselves as learners, identify with students' needs, and apply some of the social and emotional messages to their own lives as teachers. The Liberian teachers demonstrated an increased self-awareness of their emotional responses to misbehaving students. They reported controlling their emotions in those situations and making appropriate decisions regarding responses, helping to build teacher-student relationships.

The current results demonstrated that PD in neuroscience and MH has the capacity to build teacher self-efficacy, motivation, self-responsibility and other affective-motivational attitudes characteristic of competent teachers. These attitudes, measured on an internationally vetted instrument, are malleable. Consistent with the changes in attitudes, teachers self-reported an increased ability to engage and motivate learners, utilize student-centered pedagogies, and control their own emotions when managing their classes. Including neuroscience content into educator training provides teachers with necessary, foundational knowledge of students - how they learn and mature intellectually and how life experiences can support or undermine those processes.

DATA AVAILABILITY STATEMENT

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

ETHICS STATEMENT

All participants voluntarily and formally consented to be a part of the workshop impact study, conducted according to IRB protocols approved separately by the University of Liberia and Emory University. The patients/participants provided their written informed consent to participate in this study.

AUTHOR CONTRIBUTIONS

KB managed the program, developed curriculum, delivered the Tier II trainings, curated, analyzed, interpreted data, and edited the manuscript. JLC conceived of, designed and led the program and evaluation, developed curriculum, analyzed, interpreted data, and edited the manuscript. LM managed the program, developed curriculum, and delivered the Tier II trainings. SF managed the program, developed curriculum, and delivered the Tier II trainings. JM curated and analyzed quantitative data. JMD designed the curriculum, Tier I trainings and evaluation, delivered the Tier I trainings, provided the neuroscience content, analyzed and interpreted data, wrote, and edited manuscript. All authors contributed to the article and approved the submitted version.

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Training-of-Trainers Neuroscience and Mental Health Teacher Education in Liberia Improves Self-Reported Support for Students

Kara Brick[1,2†], *Janice L. Cooper*[1†], *Leona Mason*[1], *Sangay Faeflen*[3], *Josiah Monmia*[1] *and Janet M. Dubinsky*[4*]

[1] Carter Center Mental Health Program, Monrovia, Liberia, [2] Peace Corps Liberia, Monrovia, Liberia, [3] Ministry of Education, Monrovia, Liberia, [4] Department of Neuroscience, University of Minnesota, Minneapolis, MN, United States

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***Correspondence:**
Janet M. Dubinsky
Dubin001@umn.edu

† These authors share first authorship

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Education programs have been central to reestablishing social norms, rebuilding public educational institutions, and addressing public attitudes toward mental illness in Liberia following a protracted civil war and the Ebola epidemic. The aim of this study was to determine if a program combining an understanding of neuroscience with mental health literacy content could increase teachers' awareness of students' mental health issues and produce changes in teacher attitudes and classroom practices. A tiered Training-of-Trainers approach was employed. The first workshop trained 24 Liberian secondary science teachers in the neurobiology of learning, memory, emotions, stress and adolescent brain development. A Leadership Team formed from eight of the Tier I participants then adapted the curriculum, added in more mental health literacy content and led four Tier II workshops and four follow-up Refresher sessions. Participants completed a neuroscience knowledge test and surveys assessing stigma, general perceptions of people with mental illness, and burnout. A subset of Tier II teachers participated in a structured interview at the Refresher time point. Teachers in both tiers acquired basic neuroscience knowledge. Tier I, but not Tier II teachers significantly improved their surveyed attitudes toward people with mental illness. No changes were found in overall teacher burnout. Despite these survey results, the interviewed Tier II teachers self-reported behavioral changes in how they approached their teaching and students in their classrooms. Interviewees described how they now understood social and emotional challenges students might be experiencing and recognized abnormal behaviors as having a biopsychosocial basis. Teachers reported reduced use of verbal and corporal punishment and increased positive rewards systems, such as social and emotional support for students through building relationships. Refresher discussions concurred with the interviewees. In contrast to previous teacher mental health literacy programs which did not bring about a change in helping behaviors, this pilot program may have been successful in changing teacher knowledge and self-reported behaviors, improving teacher–student relationships and decreasing harsh discipline. The combination of basic neuroscience concepts with training on how to recognize mental health issues and refer students should be investigated further as a strategy to promote teacher mental health literacy.

Keywords: mental health literacy, neuroeducation, teacher professional development, stigma reduction, trauma-informed teaching

INTRODUCTION

A number of programs have been developed in Liberia as part of a concerted attempt to construct a system of care for mental health (MH). MH needs remain high among a population recovering from both civil war (1989–2003) and the Ebola outbreak (2013–2015). These programs raise awareness of MH issues among the public, train professionals and persons living with MH problems, and provide early intervention strategies (Kohrt et al., 2015, 2018; Ministry of Health, 2016; Gwaikolo et al., 2017; Liberia Center for Outcomes Research in Mental Health, 2020). To provide diagnostic and support services in a country with only a few psychiatrists, a cadre of Mental Health Clinicians (MHCs) has been trained to diagnose and treat people with mental illness (MI) (Gwaikolo et al., 2017; Kohrt et al., 2018). These MHCs represent a service that people were unaccustomed to utilize. To support prevention and early intervention, the Government of Liberia identified schools as a locus of health and health education and teachers as sources for accurate MH education, initial case finding, and referral support for students in need of MH services (Ministry of Health, 2016; Gwaikolo et al., 2017; Patel et al., 2018). In some schools MHCs are available on site or by referral.

Education is recognized as an important proximal factor for ameliorating the negative effects of personal, social and global traumas contributing to mental health problems (Patel et al., 2018). Social-emotional learning programs in schools constitute important community level practices for improving awareness of issues related to mental, neurological and psychiatric illnesses in low and middle income countries (LMIC) (Petersen et al., 2016). School based intervention programs have improved MH knowledge and to a lesser extent help-seeking but changes in attitudes did not necessarily accompany knowledge gains (Salerno, 2016). In Brazil, teachers were successfully trained to recognize and refer students with social, mental and behavioral problems (Vieira et al., 2014). A social contact-based approach, where individuals share their stories of struggling with MI and subsequent recovery, has been applied for organizations supporting people living with mental illness in Liberia, as this approach is most effective with adult audiences (Corrigan et al., 2012; Gwaikolo et al., 2017). An educational approach has been more effective with youth audiences, who, like the Liberian teachers, have had less exposure to the biopsychosocial model of MI and the neuroscience that supports this model (Corrigan et al., 2012), further influencing this choice.

Teachers are prominent among the community level resources needed to provide developmental support for resilience among youth (Luthar et al., 2015). Children with histories of exposure to war, violence and other physical and emotional trauma can often behave in ways incompatible with expected classroom behavior (NCTSN Core Curriculum on Childhood Trauma Task Force, 2012). One way to indirectly benefit children's resilience and mental health is to promote the knowledge and well-being of their teachers in order to strengthen these caregivers' ability to promote positive relationships with students (Luthar et al., 2015). Teacher support is among the community level variables more amenable to change to build systems that positively impact children's resilience (Luthar et al., 2015; Ministry of Health, 2016). In an international review of MH literacy programs for teachers, increases in MH knowledge and reductions in stigma were widely reported (Yamaguchi et al., 2020). A MH literacy training program in Malawi and Tanzania significantly increased teachers' knowledge of MH issues and improved their attitudes toward MH (Kutcher et al., 2015, 2016). Teacher MH trainings typically addressed MH signs, symptoms and how to respond (Yamaguchi et al., 2020). A few programs also included behavioral information on child development (Pacione and Cooper, 2014; Anderson et al., 2019). These programs, of limited duration – from a few hours to a day or so, left the audience requesting more training, and produced little evidence of change in teacher helping behaviors (Anderson et al., 2019).

Individuals with MI also face social consequences within educational settings. People with MI are viewed as abnormal and incompetent, suffering both stigma and lowered social status (Phelan et al., 2018). Within the school environment, affected youth perceive stigma against persons with MI from teachers, staff and peers (Moses, 2010; Bowers et al., 2013). Student achievement is influenced by teacher expectations. Low teacher expectations, often as a consequence of student behaviors, act as a self-fulfilling prophecy for low attainment. Stigmatized groups are more vulnerable to this effect (Jussim and Harber, 2005; Timmermans et al., 2018). The presence of MI and the associated externalizing or internalizing behaviors is generally associated with lowered overall academic attainment, although this does not hold for all diagnoses (McLeod et al., 2012; Dalsgaard et al., 2020). MI does not, *a priori*, preclude an ability to achieve academically (McLeod et al., 2012; Dalsgaard et al., 2020). This link between academics and social behavior remains an association and not a causal relationship (Algozzine et al., 2011; McLeod et al., 2012; Dalsgaard et al., 2020); yet teachers rate students with known emotional problems as having inadequate academic performance (Algozzine et al., 2011). When controlling for academic aptitude and for the co-occurrence among MH and behavior problems, the presence of a MH issue does not necessarily predict lowered academic outcomes, suggesting that negative educational outcomes may not result from inherent traits but rather from the social response of the schools to the presence of these problems (Algozzine et al., 2011; McLeod et al., 2012). In recent years, positive behavioral interventions and support programs have begun to ameliorate the behavioral issues and possibly improve educational outcomes (Patel et al., 2018; Sugai and Horner, 2020). School based MH literacy programs provide a mechanism for addressing both teacher expectations and needed student supports (Yamaguchi et al., 2020).

Neuroscience provides both a framework for understanding how traumatic experiences can reshape learning and relationships in a child's world and a hopeful prospect that brain plasticity nurtured in a safe school environment can produce resilience (NCTSN Core Curriculum on Childhood Trauma Task Force, 2012; Howard, 2019). Understanding the developmental neurobiology of children's brains, a core concept essential for dealing with traumatic stress responses in childhood (NCTSN Core Curriculum on Childhood Trauma Task Force, 2012), may provide an engaging entry point for raising teachers' awareness of MH issues among students. A neurobiological approach was envisioned as a way to expose teachers to a biopsychosocial model of mental health, to recognize their role in supporting children with social-emotional and behavioral challenges, and to dispel myths and misconceptions surrounding mental illnesses and epilepsy (Gwaikolo et al., 2017; Jones and Kahn, 2017). This knowledge should support efforts to ameliorate or modify student behaviors so they remain in school and excel academically (Gwaikolo et al., 2017; Jones and Kahn, 2017). Understanding brain plasticity is a component in interventions promoting growth mindsets, which teach how to apply the core ideas of brain plasticity to personal achievement, response to rejection, or conflict (Blackwell et al., 2007; Yeager et al., 2013, 2019). Such programs have demonstrated positive impacts upon student world view, academic performance and prosocial behaviors in the face of adversity (Blackwell et al., 2007; Yeager et al., 2013, 2019). Educating teachers in neuroscience has resulted in adoption of more student-centered and active-learning pedagogies, improved classroom cognitive environments and more social and emotional support for students (Dubinsky et al., 2013; Dubinsky et al., 2019). In the United States, school-based mental health awareness interventions have resulted in increased knowledge, acceptance, and help seeking behaviors among adolescents (Salerno, 2016). Students' social and emotional well-being is integrally tied to their cognitive, linguistic and academic development (Jones and Kahn, 2017). Increases in pro-social behaviors and decreases in risky behaviors and MH issues accompany positive student-teacher relationships, an increased sense of belonging, connectedness, and students' feelings of safety and being cared for Aldridge and McChesney (2018). Warm and engaging teacher–student relationships are related to greater student learning (Jones and Kahn, 2017).

Objectives

We therefore designed a training program for Liberian teachers focused upon the foundational concepts that neuroscience brings to both education and the etiology of mental disorders. For a science teacher audience, an education approach was chosen as a starting point. In an effort to maximize resources, a Training-of-Trainers approach (Kohrt et al., 2015) was employed; teachers from the Tier I workshop were expected to lead subsequent workshops for Tier II teachers. The Training-of-Trainers approach has been used successfully in training teachers in Malawi and Tanzania to use a MH awareness classroom curriculum (Kutcher et al., 2015, 2016). **Table 1** provides goals for the program and the alignment of various programmatic standards with those goals and program elements. Program evaluation focused upon the success of meeting those goals and upon the success of the training approach. Program outcomes regarding teachers affective and motivational attitudes and pedagogy (goals 2 and 3) and the translation from Tier I to Tier II appear in a companion paper (Brick et al., 2021). Here the focus is on teachers' acquisition of neuroscience knowledge (goal 1) and development of their understanding of MH issues in students (goal 4).

Teachers were expected to benefit from exposure to an understanding of the neuroscience of learning and memory, and active learning pedagogy (Dubinsky et al., 2019). The neuroscience knowledge was expected to connect with their prior knowledge, to influence both teaching practices and understanding of mental health etiology, and to eventually be transferred to students. We hypothesized that teachers would develop a view that students with social, emotional and behavior issues had the potential to succeed in the educational system. However, we did not know *a priori* if measures of stigma would change since this topic was not specifically taught. This pilot study employed a mixed methods approach using both qualitative and quantitative methods to analyze how Liberian science teachers responded to an experimental curriculum in which basic neuroscience was taught as a means for improving teacher understanding of student mental health issues. The specific research questions were:

(1) How well did Tier I and Tier II teachers learn neuroscience?
(2) How did both Tier I and Tier II trainings alter teacher attitudes toward the mental health issues of their students?
(3) How did teachers adapt their teaching to accommodate any new understanding of student mental health?

MATERIALS AND METHODS

Study Design

The current exploratory study tests if an existing intervention, training teachers in neuroscience (MacNabb et al., 2006b; Roehrig et al., 2012; Schwartz et al., 2019), can produce previously untested outcomes regarding teachers' attitudes toward the MH needs of their students. Alternatively, this study could be considered at the design and development stage as the intervention model is being expanded to include the training-of-trainers locally in Liberia (NSF, 2013). This study builds on evidence-based and evidence-informed knowledge and practices to investigate the applicability and consequences of training

TABLE 1 | Alignment of program goals and elements with various standards.

Program goal or other element	Tier I activity	Tier II activity	Standards for effective PD	Pedagogical practices developing countries	Lessons for project design in LMIC	Ministry of education goals
Goal 1: Understanding the basic neuroscience of brain function and dysfunction associated with neurological and mental disorders	Lectures (∼20% of total time)	Lectures (∼50% of total time)	Content focus	Sustained attention; Frequent and relevant use of learning materials beyond the textbook	Integrated set of mutually reinforcing activities	Production and implementation of a curriculum that is relevant, appropriate and addresses major content and quality concerns
Goal 2: Modeling student-centered teaching practices	Classroom activities, model building, experiments, discussions	Classroom activities, model building, experiments, discussions	Active learning, collaboration, use of Models	Drawing on students' backgrounds and experiences; flexible use of whole-class, group and pair work where students discuss a shared task; open and closed questioning, expanding responses, encouraging student questioning; demonstration and explanation, drawing on sound pedagogical content knowledge	Integrated set of mutually reinforcing activities	
Goal 3: Improving the pedagogical expertise and confidence of teachers	Reflection, discussion, role play and practice teaching	Reflection, discussion, role play and practice teaching	Coaching and expert support, feedback and reflection	Feedback, inclusion	Integrated set of mutually reinforcing activities	
Goal 4: Incorporating a biopsychosocial model of mental health in the teacher mindset	Discussion	Activities from the Good Schools Toolkit*; videos, discussions		Creating a safe environment in which students are supported in their learning; inclusion	Integrated set of mutually reinforcing activities	To make those provisions and arrangements that result in the school environment being clean, sanitary, violence-free and sufficiently conducive for all students, especially girls, to feel safe and at ease
Tiered training	Trained by visiting neuroscientist	Trained by Tier I leadership team	Coaching and expert support, feedback and reflection	Administrative and peer support	Wide engagement of stakeholders at all levels; capacity building	Development and implementation of an in-service program to upgrade and update trained teachers
Evaluation	Daily reflections; knowledge test; surveys	Daily reflections; knowledge test; surveys; interviews	Feedback and reflection		Monitoring and evaluation	
Duration	10 days	5 + 2 days	Sustained duration		Appropriate timeframes; sufficient resources for implementation	
Reference	Brick et al., 2021	*Devries et al., 2015, Brick et al., 2021	Darling-Hammond et al., 2017	Westbrook et al., 2013	Lehner, 2012	Ministry of Education, 2010

Liberian teachers in neuroscience. Although not perfectly aligned with this work, the SQUIRE-EDU, GREET, and SRQR guidelines have informed preparation of this report (O'Brien et al., 2014; Phillips et al., 2016; Ogrinc et al., 2019).

A mixed methods approach was used to assess the efficacy of a two tiered PD program for Liberian secondary science teachers combining neuroscience and mental health. Quantitative survey data was collected from teachers in both tiers regarding their knowledge of neuroscience and their attitudes toward people with mental illness. Qualitative data from structured interviews was collected from a subset of Tier II teachers on how they applied this knowledge in their classrooms.

Intervention

This pilot project trained a set of Liberian secondary science teachers in the neurobiology of learning and memory, emotional processing and stress, and the etiology of epilepsy and PTSD. In this two-tiered training, a visiting neuroscientist with prior experience providing teachers with neuroscience training (MacNabb et al., 2006b; Roehrig et al., 2012; Dubinsky et al., 2013, 2019; Schwartz et al., 2019) delivered a workshop (10 days over 2 weeks) for Liberian secondary science teachers (Tier I). A subset of the Tier I teachers then adapted the material for the Liberian context and delivered a series of 1-week (5 full day) workshops to train additional Tier II Liberian teachers [see below, **Table 1** and (Brick et al., 2021)]. An intensive training approach was chosen because short neuroscience exposures change very little (Howard-Jones et al., 2020) and evaluation of United States science teacher training programs determined 80 or more hours of PD were needed for teachers to enact substantial classroom changes (Lawrenz et al., 2007). The initial Tier I training occurred in August 2018, modeled after a successful program developed for United States teachers (MacNabb et al., 2006b; Roehrig et al., 2012; Dubinsky et al., 2013, 2019; Schwartz et al., 2019). Lessons plans and resources used in the workshop were drawn mainly from open internet neuroscience resources (MacNabb et al., 2006a; SFN, 2019), as recommended for educational improvement in Sub-Saharan Africa (Wolfenden et al., 2012).

A subset of eight Tier I teachers joined staff to form a Leadership Team that planned and delivered four Tier II trainings in October through December 2018. The Leadership Team selected the Tier II neuroscience content and added mental health awareness content and how to identify early warning signs of MH issues from the Manual of School Mental Health (Pacione and Cooper, 2014) and The Good Schools Toolkit (Section 3.5, Devries et al., 2015), resources specific to successful MH education in Africa. Additional internet resources were used to stimulate discussions of students' and teachers' MH issues (Brick et al., 2021). The Tier II neuroscience content was reviewed by email and approved by the visiting neuroscientist. Tier II content was approximately 50% similar to Tier I content (see Brick et al., 2021 for a more detailed discussion of workshop content and fidelity). Workshop delivery consisted of Liberian teachers training fellow Liberians. Program staff on the Leadership Team guided the team in setting standards for and maintaining content quality. In response to teacher requests for support, a series of four 2-day follow-up Refreshers were organized by the Leadership Team in March and April, 2019. On 1 day, Tier II teachers shared stories about and reflected on their teaching after the workshop and had a digital question and answer session with the visiting neuroscientist. On the other day of the Refreshers, teachers practiced teaching neuroscience lessons in local secondary schools. All sessions, except for this one Refresher day, were held in neutral meeting spaces outside of a school setting. All of these processes received support from the Ministry of Education and were overseen and hosted by an international non-governmental organization, as recommended for successful education projects in LMIC (Lehner, 2012). All events were held in Monrovia, Liberia except for one Tier II workshop and one Refresher which were held in Kakata, a small city interfacing with more rural areas of Liberia.

Participants

Secondary science teachers were chosen as the target audience because they taught to the Liberian and West African science standards that included biology and some neuroscience knowledge (W.E.A.C, 2011). In keeping with Liberian traditions and as a gesture of respect and partnership, the Ministry of Education Office of Science Education called Principals and Heads of high schools within the Monrovia Consolidated School System and Kakata Government Schools and asked them to choose one or two science teachers to send for training. This non-random process ensured that participants had appropriate backgrounds and positions (Best and Kahn, 2006). The Tier I workshops were attended by 15 high school science teachers, one university level instructor, and eight staff members from the Ministry of Education. Ninety-two science teachers attended the Tier II workshops. Participants only received compensation for transportation expenses; they were not paid for their time or effort. The majority of participants (63% Tier I, 53% Tier II) were from Montserrado County, which contains the Liberian capital of Monrovia where most of the workshops were held. Females are underrepresented among Liberian teachers (Stromquist et al., 2013) and among participants (38% Tier I, 26% Tier II). For both tiers, 63% of the teachers held BS degrees. However, 35% of Tier II teachers were without university level teacher training as opposed to 21% of Tier I participants. Teachers' educational backgrounds have been previously reported (Brick et al., 2021). Only one teacher in each tier had any prior MH training (Brick et al., 2021).

Participation in the workshops and in the data gathering were described to participants as separate processes. All participants voluntarily and formally consented on day 1 to be a part of the workshop outcome study, including to be interviewed, conducted according to IRB protocols approved separately by the University of Liberia and Emory University. Teachers were assigned alphanumerical identifiers to use instead of their names on all surveys and assessments.

Instruments

Program outcomes were measured through a mixed-methods approach that included participant daily reflections, pre-post workshop multiple choice knowledge tests, self-reported surveys and interviews. For the 24 Tier I participants, a 13 question knowledge test was administered on the first and last days of the workshop (MacNabb et al., 2006b). The Tier I survey was administered at the end of the workshop twice, once regarding how teachers felt at that time, and once projecting how they remembered feeling prior to taking the workshop. Thus a retrospective pre-survey approach was taken where respondents understand what their true initial knowledge was after they have become fluent in the provided content (Levinson et al., 1990; Bhanji et al., 2012). For Tier II, survey data were collected at three time points, on the first and last days of the weeklong workshops and at the Refreshers. Teachers in one Tier II workshop completed a shorter 4 question neuroscience knowledge test tailored to the Tier II content. Another subset of 10 Tier II teachers were interviewed by two Leadership Team members at one Refresher. The Tier II interviewees were determined by convenience and were not randomly selected. Field notes were kept for the discussions among teachers at the Refreshers.

Survey instruments were chosen to measure the impact of the Brain Science training on participants' knowledge of neuroscience (MacNabb et al., 2006b) and attitudes toward mental health issues. Scales employed for these attitudes included a version of the Social Distance scale to measure MH stigma in Liberia (Kohrt et al., 2018; Boazak et al., 2019), and a General Perceptions of People with Mental Illness scale (Kohrt and Swaray, 2011), both in Liberian English. The Social Distance scale consisted of nine statements regarding willingness to engage with someone with mental illness and uses a 4 point Likert scale of 1, definitely willing; 2, probably willing; 3, probably unwilling; and 4, definitely unwilling for a range of 9–36. The General Perceptions scale consisted of seven statements regarding ideas about or attitudes toward people with mental illness and uses a 4 point Likert scale of 1, strongly disagree to 4, strongly agree, for a range of 7–28. For both scales, lower scores indicate less prejudice. The Maslach Burnout Inventory for Educators (Maslach et al., 1996) was also included to determine if the neuroscience trainings effected burnout. This scale consisted of 22 statements expressing stress and uses a Likert scale for frequency of encountering these feelings of 0, never to 6, every day, for a range of 0–132. Lower numbers indicate less stress. Permission was granted for use of these scales.

The structured interview questions appear in the **Supplementary Materials**.

Quantitative Analysis

All surveys employed Likert scales. After reverse coding appropriate items, survey responses were summed across an entire scale and then averaged across all participants at a single time point. While Tier I and II responses were kept separate, responses across all of the Tier II workshops were aggregated. Tier I comparisons between post and retrospective pre time points were made using two tailed t-tests (Graphpad Prism, version 6.1). For Tier II comparisons among pre, post and Refresher time points, data were analyzed using one-way ANOVAs with Tukey's multiple comparison post-tests (Graphpad Prism, version 6.1). No data were discarded.

Qualitative Analysis

In-depth individual interviews were conducted in Liberian English based on a structured interview guide. These interviews were conducted at the end of one Refresher workshop with 10 participants who were teaching in the Liberian school system and who attended Tier II trainings. The interview questions explored the role of the teachers, changes and challenges in their teaching since the training, student behavior, mental health issues in the classroom, and feedback on the trainings. All interviews were digitally recorded and subsequently transcribed and annotated. Interviewers also wrote field notes.

Interviews were initially coded using NVivo 12. A framework analysis approach was applied as it was most appropriate for this multidisciplinary project and could be applied inductively without forcing a particular theoretical perspective (Gale et al., 2013). A codebook was developed after an iterative reading of the interviews to generate codes (SKF). Additional codes based on the study objectives were added to the codebook. Two authors (KB and JMD) separately coded all interviews, using the field notes for context. Three authors (KR, JMD, and JLC) then iteratively discussed and recoded the data until consensus was reached. Independently, two authors (KB and JMD) summarized the coded data in written form. These summaries were subsequently discussed among the three authors (KR, JMD, and JLC), edited and reworked until themes emerged and consensus was reached.

RESULTS

Knowledge of Neuroscience

Both Tier I and Tier II teachers' knowledge of neuroscience increased significantly after their respective workshops (**Figure 1**). Tier I teachers took a knowledge test equivalent to that used in prior trainings and scores improved comparably

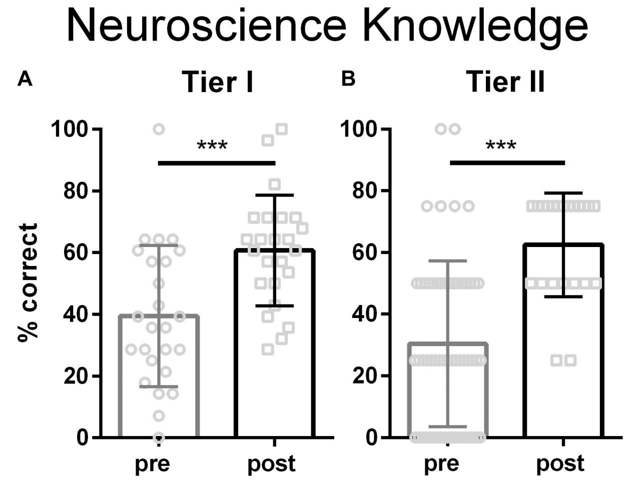

FIGURE 1 | Knowledge of neuroscience for teachers attending Tier 1 **(A)** and Tier II **(B)**. Tier I teachers took a 13 question multiple choice test (MacNabb et al., 2006b). Tier II teachers took a 4 question multiple choice test. Both Tier I and Tier II teachers significantly increased their knowledge of the neurobiology of learning and memory (Tier I, $p = 0.0007$, Cohen's $d = 1.0$; Tier II, $p < 0.0001$, Cohen's $d = 1.3$; 2 tailed t-tests). Bars are mean ± stdev; Tier I $N = 25$ pre, 24 post, Tier II $N = 60$ pre, 22 post. *** represents $p < 0.001$.

(MacNabb et al., 2006b). Since the content and length of the Tier II workshop was less than that of the Tier I workshop, Tier II teachers took a shorter knowledge test focusing only on brain plasticity. The plasticity concepts were grasped by all attendees.

Attitudes Toward Mental Health

Initially participants in both tiers scored in the middle of the range on the General Perception of people with mental illness survey scale. These scores significantly decreased at the end of the workshop for Tier I teachers (**Figure 2A** and **Supplementary Materials**), indicating fewer misperceptions. At the end of the Tier II workshop, the median score moved in the correct direction, but not significantly so (**Figure 2B**). At the Refresher time point, Tier II teachers' ratings on this scale were significantly greater than both initial and post-workshop ratings.

On the Social Distancing Scale, teachers in both tiers initially scored above midrange. The training significantly decreased Tier I teachers' negative attitudes toward people exhibiting neurodiverse behaviors (**Figure 3A** and **Supplementary Materials**). Among Tier II teachers, the training did not significantly alter ratings on this scale (**Figure 3B**). By the Refresher time point, the variability among Tier II teachers' ratings had decreased, resulting in a significant rise in negative attitudes compared to the end of the workshop. Refresher time point ratings were, however, not significantly different from the initial time point.

For the Maslach Burnout Inventory Scale for Teachers, Tier I teachers' ratings appeared slightly lower after the training, but only reached significance for the subscale on Depersonalization (**Figures 4A,B** and **Supplementary Materials**). The training did not immediately change Tier II teachers' burnout ratings on the

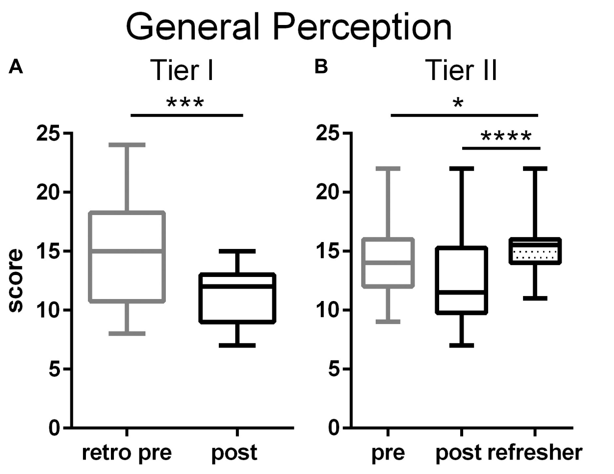

FIGURE 2 | General Perceptions of people with MI among Tier I **(A)** and Tier II **(B)** teachers. Tier I teachers significantly reduced negative attitudes toward people with mental illness after the training ($p = 0.0007$, Cohen's $d = -1.09$, two tailed *t*-test). Among the Tier II teachers, negative attitudes declined only as a trend after the training, but rose significantly at the time of the Refresher ($p < 0.0001$, $\eta^2 = 0.15$, one way ANOVA with Tukey's multiple comparison post-test). Boxes represent 25th to 75th percentiles with an internal bar at the median. Whiskers delineate maximum and minimum data points. Tier I $N = 22$ retrospective pre, 23 post, Tier II $N = 44$ pre, 38 post, 56 Refresher. For the post tests, *, ***, **** represent $p < 0.05$, 0.001, 0.0001, respectively.

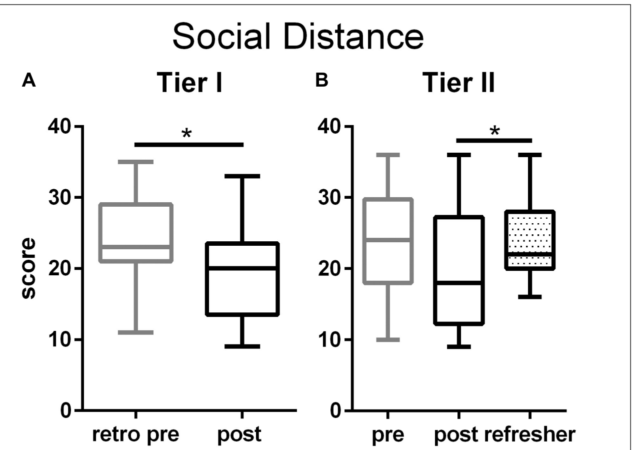

FIGURE 3 | Social distance scale among Tier I **(A)** and Tier II **(B)** teachers. Tier I teachers significantly reduced negative attitudes toward people with mental illness after the training ($p = 0.020$, Cohen's $d = -0.70$, two tailed *t*-test). Among the Tier II teachers, social distancing attitudes declined only as a trend after the training, but rose significantly at the time of the Refresher ($p = 0.031$, $\eta^2 = 0.049$, one way ANOVA with Tukey's multiple comparison post test). Boxes represent 25th to 75th percentiles with an internal bar at the median. Whiskers delineate maximum and minimum data points. Tier I $N = 23$ retrospective pre, 24 post, Tier II $N = 44$ pre, 40 post, 56 Refresher. For the post tests, *represents $p < 0.05$.

full scale or on any subscale (**Figures 4C,D**). At the Refresher time point, Tier II teachers' burn out ratings were significantly higher for the full scale and for the Depersonalization subscale. Other factors during the intervening period between the training and the Refresher may be responsible for this increase in burnout.

Teacher Interviews

Tier II teachers' attitudes toward student mental health issues were more clearly expressed in the interviews conducted at the Refresher time point. Three themes described the changes emerging from analysis of these interviews: (1) Teachers understood adolescent development and the causes of student MH issues; (2) Teachers endeavored to build positive relationships with students to address social and emotional issues; and (3) harsh disciplinary practices were abandoned in favor of inclusive practices and positive reinforcement, shifting the power dynamics within the classroom. The field notes from the Refresher discussions with all Tier II survey respondents were reviewed and found to emphasize these same three themes with enthusiastic, candid and varied examples.

Recognizing Mental Health Issues

Teachers embraced an understanding of brain development over the adolescent years. Since adolescents appear to have mature bodies, teachers may easily have assumed their mental capacities were also at adult levels. Understanding that brain plasticity and brain growth continued into early adulthood changed teachers' expectations of students. "Because as a teacher before . . . I never knew the difference between adult brain development and that of children's brain development (T9)." This foundation set the stage for a deepened awareness of student problems and mental health issues.

Teachers appreciated that abnormal behavior, either for the group or the individual, should be traced to an issue. Teachers realized that deeper problems may be indicated by the following ongoing behaviors: being withdrawn, sleepy, inattentive, uncooperative, disruptive, rude, disrespectful, or otherwise non-compliant. To recognize MH issues, teachers compared a student to peers or compared a student to their own prior behavior, observed over a longer timeline. As one astute teacher put it: "Until you are smart, until you are really following students, you will not get to know who is developing mental problems. I don't have to be a medical doctor to know that someone has some emotional problems, some personal issue. When I know my student. . . I know that this person has not been in such a mood before. . . I often refer them to a doctor (T9)." Teachers were cognizant that material and social environments outside of class can greatly affect students' mental state. These factors included poverty, home environment, overwork, lack of a supportive family, fatigue, psychological and general social or emotional issues. "[students may come to school with] some family problems, so they would just come and lay their heads down (T6)."

Teachers realized the stigmatization associated with mental illness or poor scholastic performance did not imply a student was unintelligent, hopeless or 'bad.' "Before then we used to focus too much on the brilliant students and consider those ones that still behind or slow in learning. are wasting our time. In fact, nothing good would get out of them. So sometimes we don't have patience. But since, the reception of this training, my

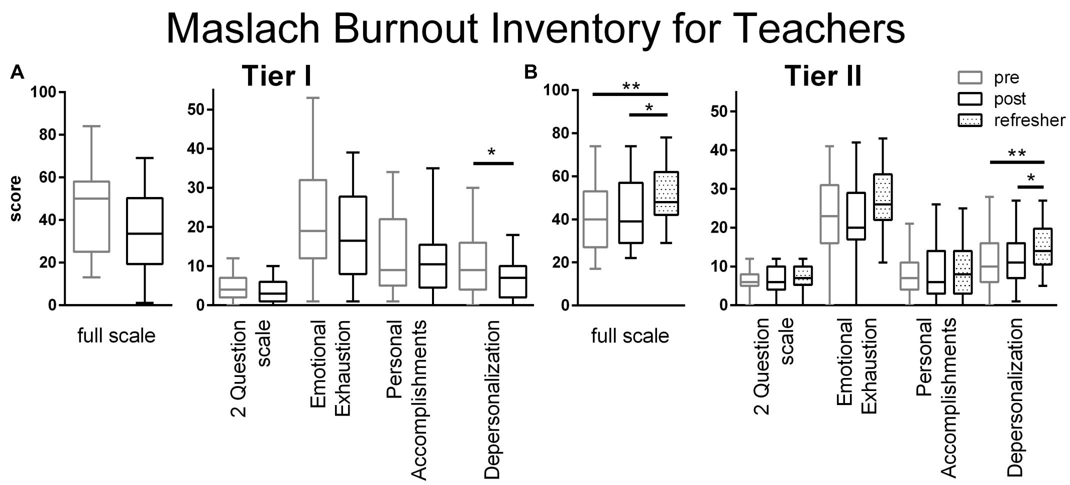

FIGURE 4 | Maslach Burnout Inventory Scale ratings from Tier I **(A)** and Tier II **(B)** teachers. Decreases in burn out scores were only observed in Tier I teachers after the training on the Depersonalization subscale ($p = 0.061$, full scale; $p = 0.269$, Two Question Scale; $p = 0.141$, Emotional Exhaustion Scale; $p = 0.457$, Personal Accomplishments Scale; $p = 0.041$, Cohen's $d = -0.61$, Depersonalization Scale; two tailed *t*-test). Among the Tier II teachers, burn out ratings increased by the Refresher (full scale, $p = 0.0019$, $\eta^2 = 0.088$; Two Question Scale, $p = 0.437$; Emotional Exhaustion Scale, $p = 0.0.038$, $\eta^2 = 0.047$; Personal Accomplishments, $p = 0.615$; Depersonalization, $p = 0.0025$, $\eta^2 = 0.085$; one way ANOVA with Tukey's multiple comparison posttest). Boxes represent 25th to 75th percentiles with an internal bar at the median. Whiskers delineate maximum and minimum data points. Tier I $N = 23$ retrospective pre, 24 post, Tier II $N = 43$ pre, 39 post, 56 Refresher. For the post tests, *, ** represent $p < 0.05$, 0.01, respectively.

mentality has completely changed (T9)." Rather they now viewed such students with potential to improve once the problem was addressed: "Everybody are equal. Maybe some people, especially for those that have mental problem, you cannot say, 'hey you move that side! Man, you rude, you're good for nothing.' No. What I learn from the training, that everyone has importance and they have their rights, and as a teacher I'm also the one to point you in the right path (T6)."

For the particular problem of epilepsy, teachers embraced explanations for its neurophysiological causes and became willing to include them in the school culture. In Africa, epilepsy could occur as a consequence of head injury, cerebral malaria or tapeworm infections among other causes (DeGiorgio et al., 2004; Klejnstrup et al., 2018). Teachers were more aware of the stigma surrounding epilepsy and the detriment it caused to such students, who suffered from social isolation, not seeking medical attention, and not being assisted when seizing. "I got a student with epilepsy, and the training I got when I went back, I just apply it right away, because we all felt [before the training] that the epilepsy was contagious, so any time it will happen, we. just shy away and look. But I went there, I told the class. in fact, I call the entire school in one of the devotion [assemblies], and we discuss what are some of the help that we can provide and what is epilepsy. We discuss that, and from there, the child is free now. He moves around, and other people go around [with] the child, in the classroom. They don't feel like, 'The epilepsy that you have, other people can contract it.' So I've helped in that direction (T7)."

Building Teacher–Student Relationships

Once students' mental health issues were contextualized and defined, teachers were willing to be patient with and give attention to students with psychological, social or emotional issues. Teachers increased their interactions with students, discussing problems, befriending them and generally helping them solve social and emotional problems. Teachers created opportunities for connection with students to provide emotional support, in particular to talk through whatever might be on their minds if they were showing signs of distress. "I interview them and they will give me their inside history. They will better explain what really they are going through, then from there, [I] start to help them. maybe they are traumatized, then I help them by talking to them. If there is something bothering them, explain the situation. Explain the situation, or through this you can help yourself, talk to them, just be able to counsel them (T5)." Teachers discerned a difference between emotional behavioral problems and those caused by underlying social issues. Teachers made efforts to provide social support by providing meals, a place to study and supplies, despite the financial hardship of often late or missing paychecks (Adebayo, 2019; Romero and Sandefur, 2019). "Students like [those in need], I try talking to them, I make myself available to give them something in the morning. Every morning I told them, 'When you come, just come, strictly in my office, I will give you something.' Because of that, this particular child always happy in the morning to come (T5)." Teachers' extra efforts and increased social support strengthened their relationships with students.

Nine out of 10 teachers related stories about helping individual students address a social, emotional or MH problem through personal involvement in providing care, constructing a care strategy with others, or through obtaining medical care. Success stories included clarifying communication in social situations, building relationships to bring students back into a state of learning, or encouraging other educators to move forward in a different way. Teachers were cognizant that MH support differs from other types of support, requiring an underlying relationship, ongoing talking, and more attention. They investigated root social or home causes of student problems. Teachers referred students to guidance counselors, discussed issues with parents, or accompanied students to seek medical or psychological attention. "Then, if it is something serious, really serious, I will try to get in contact with the student's parents. Then we together can take it from there. If it means that the student has to see a psychiatrist or a doctor, then we can do it that way, because I believe that my responsibility to search a student and not just restricted in the class. . . . Maybe the parent might not know what is happening. Cause some students are very much afraid of the parents (T9)." Despite getting more than they expected after scratching the surface of students' aberrant behaviors, these teachers remained committed to working diligently to resolve them.

Disciplinary Practices

Corporal punishment is an acknowledged component of classroom discipline in Liberia as well as in other African nations (Antonowicz, 2010). Interviewed teachers explained this historical and cultural legacy: ". . . because in the African mentality before then our teachers, those that used to teach our fathers and mothers, it was nothing different from slave and master. Yeah. They were harsh to the extent that they used to beat on students like criminals. Even up to now some of our parents got the mark [scars] (T9)." Teachers learned that 'beating' can have a detrimental effect on the physical brain: "I got to know that, especially for the little ones, if you slap them behind their head you will cause problems for the brain (T5)." Teachers admitted to having previously beaten, insulted, shamed and discouraged students: "Before the training I used to beat on students especially those slow learners, . . . also those students who have the habit of making noise in class. . . . and also I used to discourage them in class (T2)." They acknowledged that they had not allowed students time to think and had used physical or disciplinary actions in response to wrong answers.

The interviewed teachers contrasted their current practices with their admitted prior use of harsh discipline. Previously, teachers said they used practices that may have been emotionally damaging. Teachers attested to now using patience and dialog to respond to noisy or inattentive students rather than physically beating them. "For instance . . ., as an instructor in a class sometimes a student annoys you, you get angry, you call the student up . . . and slap the student's head, which is very wrong. The workshop, the training has made us to understand that such things is wrong and believe me I decided not to practice that both home and in my school that I teach (T1)." In one of the Refresher sessions, male teachers reported they had ceased engaging in forced physical relationships with female students. Teachers reconsidered the language they used with disruptive students, stopped using profanity and insults, and began using encouraging and more inviting approaches: "[before the training,] we may be insulting them and telling them . . . 'you are stupid.' Make sure, I want you to know that child is not stupid. . . . So, you as a teacher, we need to share love, patience. Create a new avenue and beginning to take more and more how to get inside to them (T10)."

Teachers shifted from presenting themselves as powerful authority figures or managers to becoming more friendly and approachable. One teacher related, "I was the kind of teacher, I was very much temperamental and very restrictive, frightening students. Well, since I came to this workshop, . . . my temper dropped a little bit. . . . I have learned a lot . . . and I have made a new trend. So at this time now students can relate to me . . . and most of these students are now participating freely in my class (T1)." Teachers switched from perceiving student behavior as a threat to their authority, to perceiving their own behavior and lack of self-control as a threat to student learning. In the words of one teacher, "In the classroom, I'm not teaching student[s] to be afraid of me any longer, I'm helping them to learn (T7)." Teachers gave considerable thought to disciplinary processes, engaged student agency and remained flexible, a departure from teacher generated rules: "But nowadays, we . . . allowing students to have a role on issues. . . . But, at the same time too, we instructors who have the ability to think and rethink and be innovative in order- when you craft a law or ground rules in the class and you understand that the vast majority are not abiding by such a rule then as an instructor, you rethink and see how best you can craft another rule that you think can govern the class . . . So there are so measures as the teacher needs to put in place, in order for the student to govern itself (T1)." Teachers recognized that giving students more autonomy to buy into the materials or rewarding good behavior would decrease the need for the previously used teacher behaviors such as becoming angry, leaving the class or expelling students. "Because at first I never knew that, beating on child or . . . let's say whenever the child having to do a positive thing, you give them . . . let's say employ a reward, I never knew that, but from this training, I get to know that (T8)." They empowered students to contribute to class through questioning and discussions (see above). Teachers endeavored to make the material less frightening and more manageable. The shift from a focus on control to a focus on success for all required flexibility, openness and emotional awareness.

Some teachers expressed difficulty in figuring out how to motivate and engage students after using the previously favored harsh discipline: "If somebody disturbs a class and you tell that person 'Stop disturbing!' and that particular student knows fully well that he or she is not [going to be] whipped . . . or . . . beaten . . ., he will always disturb. . . . We tried to design some strategies in order to curtail that. So we are working on it and gradually we are getting there (T1)." Designing new methods for classroom control took effort and concentration. Teachers were willing to analyze their situations and adapt fluidly. Going from harsh punishment to positive behavioral systems generally results in less immediate results and requires more up-front investment on the part of the teacher. This is even more difficult if a negative relationship had already been established: "because I'm not the beating type now, they find it so easy to rile (T5)." The process of implementing non-violent discipline with students previously abused or witness to abuse in school was challenging for the teachers. Encouragingly, the interviewed teachers indicated that they would persist in modeling appropriate ways to manage emotions.

DISCUSSION

Participants in both Tier I and Tier II trainings gained knowledge of brain plasticity and neuroscience, an objective outcome. As measured by the survey scales, the training may have significantly decreased Tier I, but not Tier II participants' subjective, negative attitudes and stigma toward people with MH problems. Some opinions from Tier II teachers tended to move in the correct direction after the training, only to rebound to more negative levels by the Refresher meetings. The interviewed Tier II teachers, however, described many positive changes to their practices that may have resulted from their new understanding of synaptic plasticity, adolescent brain development and the biological basis of mental illness. Notably, teachers reported reigning in their own negative emotional reactions in response to disruptive behaviors and working hard to build supportive relationships with students with social, emotional or behavioral problems. These personal accounts suggest the tiered training structure may have raised awareness of MH issues and influenced participants to re-evaluate classroom practices.

Attitude changes were registered among the Tier I cadre, but less so among the Tier II cadre. The difference in content or duration of the two trainings may have accounted for this. At the time of the Refreshers, Tier II participants' reported more negative attitudes on the General Perceptions Scale. Many programs emphasizing education or MH literacy have resulted in more negative or absence of large, meaningful attitude changes or stigma reduction, despite successfully shifting acceptance of MI as biologically based diseases (Pescosolido et al., 2010; Corrigan et al., 2012; Stuart, 2016). More successful general audience stigma-reducing interventions utilize a social contact model where previously ill individuals recount their stories and recovery (Corrigan et al., 2012; Stuart, 2016). In comparison with MH literacy programs for teachers that emphasize behavioral signs, symptoms and appropriate responses (Anderson et al., 2019; Yamaguchi et al., 2020), neuroscience training alone may be insufficient to alter stigma. However, prior programs did not necessarily produce behavioral change toward persons with MH issues (Stuart, 2016; Anderson et al., 2019; Yamaguchi et al., 2020). Only one program in Tanzania reported an increase in referrals for professional help (Kutcher et al., 2016). In contrast, in response to the neuroscience emphasis of the current program, teachers reported changing disciplinary behaviors and support for students' social and emotional needs. Thus, addition of the foundational knowledge provided by neuroscience to the behavioral focus of MH literacy programs may produce deeper learning and stronger behavioral change among teachers.

Key elements of programs aimed at reducing stigma toward MI among health care professionals include using multiple forms of message delivery, an emphasis on the ability to recover, teaching skills and behaviors for how to engage with people with MI, personal testimony and contact, myth-busting, and an enthusiastic facilitator (Knaak et al., 2014). These approaches have been implemented in other Liberian programs for health care workers, police and people living with MI (Kohrt et al., 2015, 2018; Gwaikolo et al., 2017; Liberia Center for Outcomes Research in Mental Health, 2020). The neuroscience emphasis of the current program focused upon dispelling erroneous beliefs about MI using multiple participatory forms of delivering the content by enthusiastic facilitators and practice teaching. The neuroscience emphasis sought to dispel the regionally strong, difficult to displace beliefs in witchcraft or curses as causes, and build on the strengths of students with social, emotional and behavioral problems to succeed in school (Ideanacho et al., 2014; Gwaikolo et al., 2017). The message regarding the biological basis of epilepsy appears to have been well received, internalized, and possibly translated into helping behaviors. While interviewees appeared to adopt the anti-stigma message, the overall social distancing scale results might have been improved if testimony from a recovered, affected individual had been included (Knaak et al., 2014; Thornicroft et al., 2016). Absence of sustained changes after anti-stigma program intervention, as observed here, is common, sometimes for lack of long term evaluation, but also because permanently changing attitudes and opinions remains a tenacious problem (Altindag et al., 2006; Uys et al., 2009; Thornicroft et al., 2016). Fully successful anti-stigma training programs are rare and should be culturally appropriate (Heim et al., 2019). The social burden from stigma may exceed that of the primary disease morbidity and mortality (Thornicroft et al., 2016), yet few programs effectively reduce multiple measures of stigma (Rao et al., 2019).

Disruptive student behaviors and a lack of positive teacher–student relationships contribute to teacher burnout (Skaalvik and Skaalvik, 2017). While the neuroscience training qualitatively may have impacted reported disciplinary practices and teacher–student relationships, it did not appear to alter teacher burnout. Given the overextended expectations for Liberian teachers (Adebayo, 2019), ameliorating this measure may have been overly hopeful. Surprisingly, burnout measures increased between the end of the Tier II trainings (fall 2018) and the Refresher time points (spring 2019). During this period, the Liberian economy shrank, inflation soared and the currency was devalued (African Development Bank, 2020). Teachers' pay was delayed or not received, a common occurrence (Adebayo, 2019; Johnson, 2019; Romero and Sandefur, 2019), resulting in strikes and student protests (Dunbar, 2019). Thus teachers had ample reasons outside the trainings to feel their work in schools had not been valued. Future studies should track such external systemic factors for their influence upon outcomes.

As teachers reflected that the training program appeared to influence their approach to discipline, this training program may have produced a positive impact on teachers' disciplinary behavior. Future studies would benefit from including objective measures to examine the impact of the program on this outcome. This is of particular importance given the negative impact that classroom discipline can have on students and their ability to learn – a point that teachers' comments suggested they now appreciate. Corporal punishment of children is a widespread normative practice in Liberia, as in many countries worldwide, among parents, teachers and caregivers (Antonowicz, 2010; Gershoff, 2017; EACPC, 2018). In accordance with ratification of the UN Convention on the Rights of Children in 1993, the Liberian Teacher Code of Conduct specifically prohibits both physical and verbal abuse (Ministry of Education, 2014). The 2010 National Education Sector Plan contained wording establishing that for all ages of children and youth, a school environment should be "clean, sanitary, violence-free and sufficiently conducive for all students, especially girls, to feel safe and at ease." (Ministry of Education, 2010; p. xii–xiv). Experiencing corporal punishment has been separately linked to poorer math test scores 4 years later and greater mental and behavioral problems (Jones and Pells, 2016; Gershoff, 2017). While not directly designed to address issues of interpersonal or societal violence, the program clearly resulted in behavioral changes that dialed down the level of disciplinary violence in interviewees' classrooms. Training in Uganda using the Good Schools Tool kit, developed to address violence toward children emanating from school staff, significantly reduced student reported corporal punishment after 18 months of implementation (Devries et al., 2015). Our intervention only used one exercise from this program to lead teachers in identifying the causes of student misbehavior (see section 3.5[1]) (Devries et al., 2015). Tier II teachers did, however, engage in animated discussions surrounding how to apply knowledge gained in the training to their classrooms. Simply understanding that adolescent brains and associated decision-making capability are not fully developed and therefore not equivalent to an adult's capacity, provided teachers with a strong reason to use patience in student interactions and in assessing their responses. Understanding that thinking takes time convinced teachers to pause and wait for student answers rather than rapidly punishing them for not responding.

Physical punishment, at odds with "stated" national educational policy, is common in Liberian schools (Antonowicz, 2010; Gershoff, 2017; EACPC, 2018). Interviewed teachers discussed and largely admitted to metering out harsh physical punishment as disciplinary practice. However, none of the interviews referred to gender-based violence toward students. During the Refresher discussion, several male teachers said what they learned during the training about the traumatic impact of engaging in sexual activities with students led them to cease doing so. School-related gender-based violence has been documented in Liberian schools in the aftermath of the civil war and continues into the present (Parkes, 2016). In one survey of secondary students from four Liberian counties, 43% of students reported being sexual coerced and 91% reported experiencing gender-based violence (Postmus et al., 2015). Males and females were equally at risk. Notably 27% of males and 40% of females reported having been asked for or engaged in sex as part of a transaction for better grades, school uniforms or fees, food, or money (Postmus et al., 2015). Transactional sex leads to increased social status among peers and is sometimes supported by parents as it provided a means to an education (Atwood et al., 2011; Postmus et al., 2015). Such practices persist despite the Ministry of Education 2014 Teacher Code of Conduct (Ministry of Education, 2014; Steiner et al., 2018). Considering this cultural context, statements made in Refreshers demonstrated courage, group trust, and a real commitment to change on the part of the participants sharing this information. While the neuroscience content focused upon the connections between neurophysiological stress responses and learning, the Tier II workshop content adaptations which included discussions of practices in participants' classrooms may ultimately contribute to progress on this intractable problem. These discussions demonstrate the clear benefit of appropriate cultural responsiveness and adaptation of the training to local conditions (Southall et al., 2017; Steiner et al., 2018; McCallops et al., 2019).

Trauma-informed policies and recommendations appropriately address the needs of individuals with a history of trauma and students in particular (Cole et al., 2009; Fallot and Harris, 2009; NCTSN Core Curriculum on Childhood Trauma Task Force, 2012; Trauma and Justice Strategic Initiative, 2014). For trauma-informed teaching, schools should *realize* the impact associated with prior trauma, *recognize* signs of trauma among students, *respond* in a sensitive, integrated manner, and actively prevent *re-traumatization* (Trauma and Justice Strategic Initiative, 2014). The current program may have built a *realization* of how various traumas can impact students both acutely and chronically. Teachers attested that they could *recognize* signs of mental stress among students and *respond* to those needs. Lastly, teachers actively changed their own disciplinary practices to *prevent* further exclusion and traumatization of the students. Additional guidelines proposed teachers build secure relationships with students, enhancing self-regulation, and increasing competencies (NCTSN Core Curriculum on Childhood Trauma Task Force, 2012). Tier II teachers talked extensively about building relationships with students who they formerly would have ignored. Moreover, teachers reported changing their practices to include activities that provided students with the agency to become involved in their own learning and to grow their autonomy (Brick et al., 2021). Values associated with trauma-informed care include safety, trustworthiness, choice, collaboration and empowerment (Fallot and Harris, 2009; Trauma and Justice Strategic Initiative, 2014). The student-centered pedagogies enacted by the interviewed teachers may have empowered students by giving them opportunities to collaborate with peers in group settings and exercise choice in active learning exercises. In working toward stronger relationships with their students, teachers reported building student trust in their ability to relate to the teacher, the school and to their own learning. By suspending harsh disciplinary practices, teachers reported shifting the power dynamic and created safer learning environments. Thus, the combination of neuroscience and MH topics covered many trauma-informed teaching concepts and may have produced improvements in teacher behavior consistent with these ideas.

Limitations

Two technical issues limit the interpretation of this pilot study. First, the qualitative and follow-up data collection occurred among the Tier II and not the Tier I teachers, preventing comparisons at the extended time point between the cadres.

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Second, the Tier II teachers responded to the surveys at three times, prior to and at the end of the workshop and again at the Refresher training, whereas Tier I teachers only responded to the survey at the single end-of workshop time point. In doing so, Tier I teachers' new knowledge may have allowed them to assess their positions on the various scales currently and more accurately state what their positions were prior to the training. This retrospective view acknowledges what has been learned and does not overvalue naïve initial conceptualizations (Levinson et al., 1990; Bhanji et al., 2012). If recalibration to a new normal becomes established as a result of the training, follow-up responses might fail to register change. Employing a retrospective survey might ensure that a respondent did not recalibrate their responses between initial training and follow-up.

Several other limitations impact interpretation of the current findings and should be addressed in subsequent endeavors. The non-randomized, uncontrolled nature of this pilot study means that the current model and results cannot be generalized without more rigorous testing using a randomized experimental design with control groups. The ability of the neuroscience content to motivate behavioral teacher changes should be compared to MH training without a neuroscience component. Individual teachers were targeted for the training, placing a burden on them to implement and translate the new ideas to their own schools, where local culture works strongly against change. Recruitment to the current program by heads of schools followed local customs but did not produce a random sample of teachers, which may have introduced a selection bias. Different findings may emerge among training participants who are self-selected. For larger tests of this model, randomization by schools and inclusion of controls should be considered. In that way, future programs could also target administrators and teacher cadres from the same schools to provide communities of local support for continued application of workshop ideas (Devries et al., 2015). As secondary science teachers, workshop participants were among the most educated group of teachers in Liberia. Spaced trainings with more behavioral support might be needed to similarly impact the majority of Liberian teachers. Follow-up data collection focused only on teacher attitudes and self-reported practices. We were unable to document if teachers indeed conveyed neuroscience ideas to learners. Future teacher trainings should identify and examine effects upon pedagogy, classroom environment, and student opinions, performance and resilience, measures that go beyond self-report. In addition, measures should be adopted to probe in a more structured manner the themes that emerged from the qualitative analysis; corporal punishment, disciplinary actions and transactional sex.

Recommendations and Conclusion

The positive behavioral changes reported from this pilot program merit more rigorous testing and reproduction on a larger scale. Efforts to train more teachers may require dedicated teacher coaches, government action and administrative structure (Gove et al., 2017). Future programs should consider strengthening the combined neuroscience and MH literacy program through inclusion of people with lived MI experiences as co-trainers (Corrigan et al., 2012). More practice using positive behaviors for handling discipline problems would be helpful. Confidentiality, tactfulness, and abuse are among additional topics that could be included. The program did not emphasize, but perhaps should include discussion surrounding placing teachers' responsibilities and responses within the boundaries of confidentiality. Teachers requested inclusion of more content regarding the effects of neuroactive drugs, more dissections, more practicums and more collaborative discussions. Addressing an audience of administrators and groups of teachers from the same schools would create opportunities for change throughout the educational system. Continuing the training, spaced over multiple years, would strengthen teachers' own learning and work to build strong communities of practice. The Training-of-Trainers model was feasible and potentially more cost effective than the privatization of entire schools for implementing pedagogical reforms (Romero and Sandefur, 2019).

This pilot study provides initial evidence that combining basic neuroscience and MH training may bring about behavioral changes among secondary science teachers in a LMIC. The key neuroscience concepts covered included brain plasticity, adolescent brain development, how stress and emotional states modulate learning, and the etiology of epilepsy and MH problems in Liberia. The key MH information focused on how to recognize and refer students with social, emotional, behavioral and mental health issues. The qualitative evidence pointed to apparent changes among these particular teachers in understanding of students MH and efforts to build positive relationships with students. Helping behaviors and overall social and emotional support appeared to increase, both for MH issues and normal learning. Reported use of abusive behaviors by participant teachers decreased. These qualitative behavioral changes may be the more important and lasting outcomes. Whether or not such changes could be generalized to a larger group of teachers cannot be determined without further program modification and replication.

DATA AVAILABILITY STATEMENT

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

ETHICS STATEMENT

The studies involving human participants were reviewed and approved by Institutional Review Boards of Emory University and the University of Liberia. The patients/participants provided their written informed consent to participate in this study.

AUTHOR CONTRIBUTIONS

KB managed the program, developed curriculum, delivered the Tier II trainings, curated, analyzed, and interpreted data, and edited the manuscript. JLC conceived, designed, and led the program and evaluation, developed curriculum, analyzed and interpreted data, and edited the manuscript. LM and SF managed the program, developed curriculum, and delivered the Tier II trainings. JM curated and analyzed quantitative data. JMD designed and delivered the curriculum and Tier I trainings, provided the neuroscience content, analyzed and interpreted data, wrote and edited the manuscript. All authors contributed to the article and approved the submitted version.

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SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fnhum.2021.653069/full#supplementary-material

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The Learning Styles Neuromyth Is Still Thriving in Medical Education

Philip M. Newton, Hannah Farukh Najabat-Lattif, Gabriella Santiago and Atharva Salvi*

Swansea University Medical School, Swansea University, Swansea, United Kingdom

Learning Styles theory promises improved academic performance based on the identification of a personal, sensory preference for informational processing. This promise is not supported by evidence, and is in contrast to our current understanding of the neuroscience of learning. Despite this lack of evidence, prior research shows that that belief in the Learning Styles "neuromyth" remains high amongst educators of all levels, around the world. This perspective article is a follow up on prior research aimed at understanding why belief in the neuromyth of Learning Styles remains so high. We evaluated current research papers from the field of health professions education, to characterize the perspective that an educator would be given, should they search for evidence on Learning Styles. As in earlier research on Higher Education, we found that the use of Learning Style frameworks persist in education research for the health professions; 91% of 112 recent research papers published on Learning Styles are based upon the premise that Learning Styles are a useful approach to education. This is in sharp contrast to the fundamental principle of evidence-based practice within these professions. Thus any educator who sought out the research evidence on Learning Styles would be given a consistent but inaccurate endorsement of the value of a teaching technique that is not evidence based, possibly then propagating the belief in Learning Styles. Here we offer perspectives from both research and student about this apparent mismatch between educational practice and clinical practice, along with recommendations and considerations for the future.

Keywords: evidence based education, neuromyth, VARK learning style, Kolb, medical education

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Guilherme Lepski,
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Nathan Emmerich,
Australian National University, Australia
Chariklia Tziraki-Segal,
Hebrew University of Jerusalem, Israel

****Correspondence:***
Philip M. Newton
p.newton@swansea.ac.uk

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INTRODUCTION

In educational theory, an individual's Learning Style is normally identified via a questionnaire which asks learners about their preferences for the way they learn, often using terms and theories that give the impression of being derived from the neuroscience of cognition (Coffield et al., 2004). Up to 70 different instruments are used in this way (Coffield et al., 2004). Amongst the most common are the VARK (Visual, Auditory, Read/Write, Kinesthetic) classification, along with Kolb's Learning Styles Inventory and a similar system developed by Honey and Mumford (Newton, 2015). Upon identification of a preferred style, one interpretation of the theory is then that learners will achieve more if they are taught, and study, using their preferred style. This hypothesis, known as the

Meshing or Matching hypothesis (Pashler et al., 2008) has been tested repeatedly and shown *not* to result in improved learning (Krätzig and Arbuthnott, 2006; Massa and Mayer, 2006; Pashler et al., 2008; Papanagnou et al., 2016; Aslaksen and Lorås, 2019; Rogowsky et al., 2020), and the reliability of the underlying preferences is often weak (Coffield et al., 2004). This misapplication of the neuroscience of learning to education has led to Learning Styles being portrayed as a "neuromyth" (Dekker et al., 2012). Belief in neuromyths has been extensively studied. Findings from our recent systematic review suggested that ∼89% of educators believe that matching instruction to Learning Styles will result in improved instruction, although there some methodological concerns about the studies reviewed (Newton and Salvi, 2020).

There is much we do know about the neuroscience of learning that could and should be applied to medical education. We know that human working memory is very limited, and that this represents a bottleneck for learning which can be managed via the techniques used in Cognitive Load Theory (Young et al., 2014). We know that the use of practice tests and other strategies that promote retrieval from long-term memory are very effective when studying clinically related topics (Dobson et al., 2017, 2018) and their use is associated with improved performance on clinical licensing exams (Deng et al., 2015). Unfortunately there is often a disconnect between good research evidence, policy and practice in Higher Education (Newton et al., 2020), and in particular, a gap between the neuroscience of learning, and educational practice (Howard-Jones, 2014).

Healthcare is a field where evidence-based practice is the gold standard (Sackett et al., 1996). It would seem reasonable to assume that the *teaching* of clinical practice would be held to a similar standard. However, a recent survey of educators showed that the most widely used teaching technique, by far, was based upon Learning Styles (Piza et al., 2019).

Thus the concept of Learning Styles appears to be an appealing one, perhaps in part due to its perceived focus on the student as an individual, even though individuals end up being lumped into 3–4 "styles." However, healthcare training is complex. There are multiple avenues of learning required: physical dexterity, for clinical examinations and procedures; a broad understanding of multiple sciences, to be easily recalled and applied to understand complex, highly specified subjects; retention and recall of minute details of investigations and pathologies; and finally, the communication, research, compassion, empathy and diplomacy skills required for patient care. This list is by no means exhaustive. However, it does highlight one of the obvious limitations with Learning Styles theory; the mastery of these topics requires multiple sensory domains. A student who is diagnosed as an auditory learner and then tries to master dermatology using podcasts is unlikely to succeed.

One potential explanation for the persistent belief in Learning Styles is that the evidence base is itself dominated by papers which mistakenly endorse the approach, and so an educator who seeks out the "evidence" for the use of Learning Styles is given a misleading perspective. Testing this hypothesis was the basis for some of our earlier work in Higher Education (Newton, 2015), where 89% of research papers identified, about Learning Styles, in 2013–2015, mistakenly endorsed their use.

Here we repeat and extend that 2015 study, with a particular focus healthcare education. We also offer the perspective of both education research, and medical student, considering the impact of our findings on the field healthcare education as a whole.

METHODS

We followed methods used in an earlier study about Higher Education (Newton, 2015). Thus our basic research question was to characterize the picture that a Health Professions Educator would encounter were they to search the education research literature for papers about Learning Styles. As in the previous study, the inclusion criteria and analysis questions were initially applied to the abstract. If they could not be answered from the abstract, then the full text was consulted. Full text was only assessed where freely available via PubMed Central, ERIC or Google Scholar; if a subscription or payment was required, then the result was not included because access to them would vary considerably between individual health professions educators.

Two major databases were used to identify research papers; PubMed, a database focused on biomedical and life sciences, and Education Resources Information Centre (ERIC), focused on education research and information.

The term "learning styles" was the only search term used for both databases. The search was undertaken in September 2020.

Inclusion Criteria

1. Published in the English language.
2. Published after July 2015, so as to avoid overlap with the previous study.
3. Study population from healthcare professions, e.g., medical students or qualified professionals. This included disciplines such as anatomy, pharmacy, dental, and veterinary. Review papers about health professions education were included.
4. Paper included reference, within the text of the paper, to a defined Learning Styles instrument, as listed in Coffield et al. (2004), or obviously derived from one of these instruments (e.g., the "Paragon Learning Styles Instrument" derived from the Myers-Briggs Type Indicator; Yielder et al., 2021). We did not include papers that were about "styles of learning" or other forms of personalized learning.
5. The following three analysis questions could be answered as a yes or a no.

    a. *Did the study begin with positive intent?* Would a health professions educator be more likely than not to conclude that a premise of the study was that the use of a learning styles instrument was a useful educational approach. This could be explicit or implicit.
    b. *Did the study end with a positive view of learning styles?* Would a health professions educator be more likely than not to conclude, having read the study, that the use of a learning styles instrument was a useful

educational approach. This could be explicit or implicit. Thus studies which tested (for example) a relationship between academic achievement and Learning Styles, and found no relationship, but then advocated for further research on the topic, would be considered to have a positive outcome.

c. *Did the study test the "matching hypothesis"?* The matching (or meshing) hypothesis states that matching instructional activities to a supposed Learning Style will improve outcomes for individual students. This has been tested repeatedly and been shown not to work as cited earlier. Here we determined whether any studies also tested the matching hypothesis, and if so whether the results contradicted the established findings cited above that matching does not result in improved educational outcomes.

One important difference between the present study and the 2015 study was that included studies did not have to be explicitly *about* Learning Styles, just that the study had to name a specific Learning Styles instrument from Coffield et al. (2004). This change was made to test the research question more fully; a paper which endorses and encourages (or not) the use of Learning Styles will still perpetuate the myth even if it is not specifically about Learning Styles, for example papers which are testing an educational intervention and ask participants to complete a Learning Styles questionnaire as part of the evaluation.

We also identified the specific study population, country of origin and Learning Style framework used. All data were extracted by a minimum of two assessors. Any disagreement was resolved through discussion.

RESULTS

The initial search returned 337 results. After eliminating duplicates and studies that were included in Newton (2015), 308 results remained. Of these, 112 met the inclusion criteria for analysis. Of note was that only 10 papers were excluded for being behind a Paywall, suggesting that the bulk of the Learning Styles literature is freely available and thus there would be little incentive for a casual reader to pursue paywalled research.

Positive Intent

109/112 (97%) of the papers started with a positive intent toward Learning Styles, i.e., a health professions educator reading the paper would, on balance, conclude that the authors initiated the study with a view that to use a Learning Styles instrument was a useful thing to do.

Positive Outcome

102/112 (91%) of the papers concluded with a positive intent toward Learning Styles, i.e., a health professions educator would, on balance having read the paper, conclude that to use a Learning Styles instrument was a useful thing to do.

Did the Study Test, and If So Contradict, the Meshing Hypothesis?

Only one study (Papanagnou et al., 2016) tested the Meshing Hypothesis using a recognized Learning Styles instrument. This study found no evidence to support the Meshing Hypothesis.

The most common Learning Styles instruments were the VARK system or variants thereof (e.g., VAK) (40/112, 36% of papers) and Kolb Learning Styles Inventory (35/112, 31%). Students were the most common study population, in particular Medical (36/112, 32%) and Nursing (17/112, 15%) students. The papers were from all over the world, but the United States was the most common study site (26/112, 23%).

DISCUSSION—STUDENT PERSPECTIVE (HNL)

As a medical student, the attraction of learning style frameworks are abundantly clear. Whilst my voice may at times appear discerning, I have personally—and multiple times—resorted to varying learning style quizzes and frameworks, seeking illumination and higher decile rankings in the form of colorful infographics... Ones often paired with promises of maps to academic success being a paywall of "only $70!" away.

Whilst amusing to reflect on, the reality of such instances is that they are borne of anxiety; paired, more often than not, with an uncomfortable need for academic validation which learning styles can offer in easy abundance. The personal preference for not wanting to run on a treadmill whilst reading from a textbook suddenly becomes proof of not being a "kinesthetic learner"; active listening becomes an auditory learning style. Clouded judgment at the hands of stress, anxiety and an overwhelming study load are waived away by the promise of a definitive answer, one that we, as medical and healthcare students, are taught to seek. In a field where such a vast body of information is required to be approached, digested and mentally filed at breakneck speed, such personalized, definitive answers may easily appear as a welcome relief.

The notion that such an innate aspect of the approach to clinical teaching is poorly evidenced is shocking, even bordering the hurtful and alarming. This is particularly true within a profession taught to rely so heavily on peer-reviewed evidence and learning.

Establishing the extent of this myth and responding accordingly is vital not only to medical and healthcare students' wellbeing, but also the future of careers—including teaching—of many. To consider that the entire basis of our education is not as thoroughly examined as the curriculum itself, feels like a failure; and in a world of increasing fake news and hostility toward scientific evidence, seems irresponsible to perpetuate.

GENERAL DISCUSSION

Our findings demonstrate that an educator who was interested in understanding the evidence base for Learning Styles in Health

Professions Education, and thus searched for relevant research literature, would be presented with a very misleading picture with 91% of papers presenting a positive view of the use of Learning Styles instruments.

This picture is compounded by studies in respectable journals that appeared to use experimental designs, finding significant results, but without directly testing the matching hypothesis. For example, Micheel et al. (2017) undertook a trial to test the effect of modifying an existing learning resource into multiple revised versions which were designed to accommodate preferred Learning Styles. A control group using the existing, text-based learning resource. The group that utilized a version of the resource that matched their preferred learning style did significantly better on a knowledge post-test ($P = 0.004$). Using the data presented by the authors we were able to calculate a standardized effect size which suggested that the effect was very modest ($d = 0.06$). These sorts of findings are nevertheless persuasive; this was an experimental study, conducted using a trial methodology, showing a significant improvement when participants engage with resources that match their preferred Learning Style? However, these data fail the key criteria articulated by Pashler and co; the control resource is all text. The versions used in the intervention are multimedia presentations that appear to be much more engaging; thus any improvement seen may simply be because the revised versions are just better educational resources, independent of Learning Style. Similar findings were published by Anbarasi et al. (2015) who compared the effects of a variety of different instructional materials, matched to VAK learning styles, with a "traditional group" "taught with the routine didactic lecture using PowerPoint images without pictures, videos, or animations."

The picture is further complicated by the apparent similarities between the terminology of Learning Styles, and the language of educational neuroscience and psychology. For example, one study proposed to test the meshing hypothesis (Lehmann and Seufert, 2020) but did not use a Learning Styles instrument as defined by Coffield et al. (2004) However, they did test learners *"preferences for auditive versus visual stimuli"* using a 12-item questionnaire previously published in the German language. They then randomly assigned participants to receive visual (text) or auditory versions of a 661-word text passage, followed by measures of comprehension and cognitive load. Visual learners appeared to perform better with visual (text) material with no effect in the auditive/auditive learners. The sample here was small ($N = 19$ for auditive, 23 for visual, then split into two groups for analysis) and there is a risk of both type-1 and type-2 error (e.g., the auditory material appears to be more difficult to comprehend for all learners according to the cognitive load scores). Differential preference for, specifically, visual versus verbal content does seem to be supported by evidence, in a literature that refers specifically to cognitive "style" (Mayer and Massa, 2003), although it does not appear to impact learning achievement (Massa and Mayer, 2006).

However, the vast majority of studies did not actually test the efficacy of Learning Styles, they were instead based upon an assumption that the use of Learning Styles was a good thing. For example, a common approach was for researchers to use a Learning Styles instrument with a particular group of students studying a particular topic, and then make recommendations for changes to the teaching of that topic based upon the results.

What could, or should, be done about the persistence of this neuromyth, in a discipline for which evidence-based practice is the gold standard? A recent survey study of health professions educators found that Learning Styles was the most popular teaching technique, even when compared to aforementioned techniques which are obviously effective (Piza et al., 2019). The fact that future doctors, nurses, pharmacists etc. are still being taught using ineffective methods, supported by misleading research, is alarming. Telling educators that the techniques they believe in are ineffective is a painful message, and one that can backfire (Newton and Miah, 2017), but Learning Styles show no sign of going away. The very high belief in Learning Styles demonstrated by educators around the world does not appear to be declining over time (Newton and Salvi, 2020). The bias of research toward Learning Styles is similarly not declining; in 2015 we found that 89% of papers about Learning Styles presented a misleading positive view, and most of those were from medical education (Newton, 2015). Here 5 years later it is 91%, with dozens of papers still being published every year.

If you have got this far in reading our Perspective paper then it is likely that you also care about this, and care about teaching generally. Spread the word. Advocate for teacher development sessions where fellow educators are taught about effective approaches to Learning and Teaching (Newton et al., 2020), and maybe gently, constructively, kindly, steer your peers in a different direction when they propose the use of Learning Styles.

DATA AVAILABILITY STATEMENT

The original contributions presented in the study are included in the article/**Supplementary Material**, further inquiries can be directed to the corresponding author/s.

AUTHOR CONTRIBUTIONS

PN designed the study, extracted data from every manuscript, analyzed the data, and wrote the manuscript. HN-L extracted data from every manuscript and wrote initial draft of the manuscript. GS undertook database searches and undertook pilot data analysis. AS undertook pilot data analysis. All authors reviewed the manuscript.

SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fnhum.2021.708540/full#supplementary-material

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ORIGINAL RESEARCH
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Neuroscience Concepts Changed Teachers' Views of Pedagogy and Students

Zhengsi Chang[1], Marc S. Schwartz[2], Vicki Hinesley[2] and Janet M. Dubinsky[3]*

[1] School of Behavioral and Brain Sciences, The University of Texas at Dallas, Richardson, TX, United States, [2] College of Education, The University of Texas at Arlington, Arlington, TX, United States, [3] Department of Neuroscience, University of Minnesota, Minneapolis, MN, United States

Advances in neuroscience reveal how individual brains change as learning occurs. Translating this neuroscience into practice has largely been unidirectional, from researchers to teachers. However, how teachers view and incorporate neuroscience ideas in their classroom practices remains relatively unexplored. Previously fourteen non-science teachers participated in a 3-week three credit graduate course focusing on foundational ideas in neuroscience. The current work was undertaken to gain insight into if and how individual teachers choose to later apply the proposed set of educational neuroscience concepts (ENCs) in their classrooms. This qualitative follow-up study examined commonalities in how teachers of diverse ages and subjects utilized their new neuroscience understandings. To this end, a year after the course, all participants assessed their perceived usefulness of the ENCs in a survey. Six of those teachers permitted classroom observations and participated in interviews that focused on how the ENCs may have influenced their lesson planning and teaching. The survey revealed that irrespective of subject areas or grade levels taught, teachers found the ENCs useful as organizing principles for their pedagogy now and in the future. Overall teachers estimated that the ENCs' influence on lesson design had increased from 51% prior to the course to an estimated 90% for future lessons. A cross-case analysis of classroom observations and interviews revealed how teachers used ENCs to inform their pedagogical decisions, organize actions in their classroom, influence their understanding of students, and respond to individual contexts. Teachers recognized the importance of student agency for engaging them in the learning process. The ENCs also offered teachers explanations that affirmed known practices or helped justify exploring untried techniques. The foundational neuroscience concepts offered a small group of teachers a lens to reconsider, re-envision and re-design their lessons. Some teachers applied these ideas more broadly or frequently than others. This case study provided insights into how teachers can directly apply neuroscience knowledge to their practice and views of students.

Keywords: neuroeducation, Mind Brain and Education, professional development, educational neuroscience, teacher practice, pedagogy

Edited by:
Guilherme Lepski,
University of São Paulo, Brazil

Reviewed by:
Dawit T. Tiruneh,
University of Cambridge,
United Kingdom
Franco Zengaro,
Jacksonville State University,
United States

Correspondence:
Janet M. Dubinsky
dubin001@umn.edu

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INTRODUCTION

Neuroscience and education have been struggling to determine their conceptual and practical relationship for a generation (Cruickshank, 1981; Bruer, 1997; Goswami, 2006; Meltzoff et al., 2009; Carew and Magsamen, 2010; McCandliss, 2010; Sigman et al., 2014; Bowers, 2016; Howard-Jones et al., 2016; Feiler and Stabio, 2018). Some researchers (Bruer, 1997; Bowers, 2016) argued that bridging neuroscience and education requires training in science, thus the translation of neuroscience to education cannot be implemented by teachers, but via middle ground domains such as psychology. Neuroscientists investigate the neurophysiological underpinnings of behaviors that are fundamental for education like learning, memory, attention, motivation, etc. and of disorders relevant to education like ADHD, dyslexia, dysgraphia, etc. (Goswami, 2006; Sigman et al., 2014; Howard-Jones et al., 2016). Cognitive scientists investigate knowledge construction from theoretical, neurophysiological, and behavioral perspectives (Howard-Jones et al., 2016). Educational psychologists and researchers investigate the knowledge, pedagogy, and best classroom practices needed by teachers (Good and Brophy, 1995; Im et al., 2018; Lavigne and Good, 2019). Therefore, in the debate over how neuroscience should influence education, teachers often take a secondary role. While teachers' desires to learn neuroscience have been documented and acknowledged (Pickering and Howard-Jones, 2007; Hook and Farah, 2013), teachers participate as subjects in the research endeavors or do small scale action-research on their own (Churches et al., 2020; Wright, 2020) but are rarely granted agency in conducting research (Juuti et al., 2021) or in determining how neuroscience could, should, or does influence education (Dubinsky et al., 2013; Tan and Amiel, 2019).

The *researcher-initiated* neuroscience applications have also generated philosophical and pragmatic issues for teachers. The first general epistemological concern is that laboratory findings do not easily translate into classroom recommendations because classroom dynamics are too complex and fluid to assume that researchers can offer teaching decisions to teachers (Bruer, 2006; Bowers, 2016). A second related pragmatic issue involves the manner in which teachers acquire neuroscience knowledge, through a didactic process or a constructivist one. Within a didactic setting, teachers are more likely to need translation and guidance to understand the neuroscience (Tham et al., 2019) or to be told how neuroscience should be translated into practice (Hardiman, 2012; Churches et al., 2017). Within a constructivist setting, teachers may make personal meaning by combining the neuroscience and their own insights to the relevant contexts of their classrooms (Pickering and Howard-Jones, 2007; Dubinsky, 2010; Dommett et al., 2011; Hardiman et al., 2012; Dubinsky et al., 2013, 2019; Hook and Farah, 2013; Tan and Amiel, 2019).

We recognize the *teacher-initiated* application as a promising approach since teachers ultimately make all classroom decisions (Bishop, 2008). In making classroom decisions, teachers consider their knowledge of students, theoretical understanding of education and beliefs as well as immediate and planned classroom goals and actions (Shavelson and Stern, 1981; Clark and Peterson, 1986; Shulman, 1987; Schoenfeld and Kilpatrick, 2008). Teacher beliefs may act as filters for interpreting events, frames for conceptualizing a teaching strategy or problem, or guides for intended or immediate actions (Fives and Buehl, 2012). Despite the contemporary emphasis promoting rational, data-based decision making (van der Scheer et al., 2017), many teachers rely heavily upon intuitive expertise, gleaned from years of experience, to make classroom decisions (Vanlommel et al., 2017). Indeed, teachers' own theories regarding teaching and learning often drive their decision making (Bishop, 2008; Borko et al., 2008; Bullock, 2011). While teachers can be successfully trained to use and evaluate student data as a basis for decision making (van der Scheer et al., 2017), such data is not always available for consultation when decisions have to be made in the moment during instructional interactions. Teachers learn from the trial and error process of their own teaching year after year. Evaluating such personal experiences and classroom data within professional learning communities can produce insights supporting evidence-based decision making, a process termed action-research (Little, 2007; Wright, 2020). These endeavors emphasize teacher agency in applying their broad background knowledge of students, best practices, and current policies to instructional practices.

The current study pursues this *teacher-initiated* perspective, where teachers determine if or how neuroscience influences their situated pedagogical decisions. Clement and Lovat (2012) asserted that only teachers could truly demonstrate whether neuroscience could influence education. In their view, the ultimate test for the relevance of neuroscience to education should be whether neuroscience knowledge provides teachers with "usable knowledge" that can affect the pedagogical decisions they make in their own classroom practices. Neuroscience may not provide immediately useful knowledge for classroom teaching, because neuroscience describes natural phenomena and processes while education prescribes pedagogical decisions to improve learning outcomes. However, neuroscience may indirectly affect education by bringing insights into teaching and learning that take into account the biological and physiological constraints upon these processes imposed by our brain and body. Such background information falls under Shulman's designation of *Knowledge of Students* as one of the seven necessary categories of teacher knowledge (Shulman, 1987). Clement and Lovat (2012) further argued that once neuroscience knowledge is shared in a more accessible way, teachers could play a critical role in identifying what neuroscience knowledge is pertinent and applicable to their own classroom decisions and practices.

A variety of outcomes have been reported from programs which introduce neuroscience knowledge to teacher audiences. At the knowledge transfer level, teachers want the neuroscience explained in an accessible and easily applied manner (Tham et al., 2019). A short didactic neuroscience introduction may cause teachers to think about the teaching habits they had acquired (Howard-Jones et al., 2020). Formal teacher preparation programs have embraced inclusion of neuroscience as fundamental background knowledge (Deans for Impact, 2015) and are beginning to evaluate those enactments (Friedman et al., 2019; Luzzato and Rusu, 2019). For in-service science teachers, professional development (PD) programs in neuroscience influence pedagogy, in that classroom observations revealed increased inquiry-based pedagogy and improvements in the classroom cognitive environment characterized by increased higher-order thinking, deep knowledge, substantive conversations, and connections to real world problems (MacNabb et al., 2006; Roehrig et al., 2012). In-service neuroscience PD resulted in increases in self-reported teacher self-efficacy and increased use of student-centered practices (Brick et al., 2021a). However, the PD in the latter three studies was also delivered utilizing constructivist approaches, so the teachers' behavioral and pedagogical changes may not be attributable to neuroscience alone. These studies do suggest that neuroscience knowledge might be influential in convincing teachers of the merits of constructivist teaching approaches. In focus and lesson study groups, teachers connect ideas from basic neuroscience to their own pedagogical practices (Dubinsky et al., 2013; Tan and Amiel, 2019; Tan et al., 2019). After a master's course focusing upon the neuroscience of learning and memory, non-science teachers explained their revisions to a lesson plan utilizing neuroscience ideas (Schwartz et al., 2019). Understanding biologically how stress and trauma can suppress learning, teachers self-reported curtailing harsh disciplinary practices and providing more student social and emotional support (Brick et al., 2021b). In the reflective and iterative lesson study process, providing grade school teachers with understanding of neuroscience principles guided them to shift their pedagogies to more student-centered practices and afforded them with the means to explain those choices (Tan and Amiel, 2019; Tan et al., 2019). These studies suggest that neuroscience ideas may indeed have influenced teachers' pedagogical choices. However, the majority of measures reported to date were either strictly observational, planned, or self-reported, after-the-fact information about pedagogy. Only the lesson study research, which included observation, mentored feedback and reflection (Tan and Amiel, 2019; Tan et al., 2019), has addressed if or how the neuroscience ideas influenced teachers' thinking and actions regarding their instructional choices as they were teaching.

To explore if and how teachers translate into practice neuroscience ideas encountered in coursework, observation of their classroom implementations combined with their explanations of those applications are required. Such teacher-initiated actions would constitute evidence to satisfy the criteria established by Clement and Lovat (2012) for a direct connection between neuroscience and education. To do this, we revisited a cohort of teachers who had taken a three credit graduate course taught using a constructivist approach to develop teacher basic neuroscience knowledge (for details of the intervention, see Schwartz et al., 2019).

In the course evaluation, we used ten Educational Neuroconcepts (ENCs) crafted for an audience of educators in areas such as memory, learning and emotions. These neuroconcepts represent a synthesis of neuroscience research that offers insight into basic or general principles of how the brain creates behaviors (**Supplementary Table 1**; Society for Neurosicence, 2008; Dubinsky et al., 2013). The ENCs are more than a series of independent concepts teachers need to understand about how brains function. Together they represent the complexity of human brains and neuroscience function. No one concept captures the entirety of brain function, nor do all ten. The ENCs were written as an overview of the foundational neuroscience knowledge for teachers to understand how learning occurs, and how memory, emotions and context mediate learning in their students' brains. In their initial conception, teachers were free to navigate the ENCs in the context of their own practices as their understanding of neuroscience permits (Dubinsky et al., 2013). How these principles might operate to influence teacher thinking and execution of their lessons remains unexplored. Were these ideas useful and applicable on a daily basis? If so, the ENCs might be appropriate for guiding content choices in pre-service neuroscience coursework or in-service PD. If not, then the usefulness of spending precious training time on neuroscience would be questioned.

Previously, we documented how the ENCs influenced teachers' thoughts about their lesson planning (Schwartz et al., 2019). The course did not claim that neuroscience justified any particular classroom approach. Applications of neuroscience ideas were left to the teachers who have expertise in the art of teaching and how to consider the contexts and policies of their specific classrooms. While the study demonstrated that for 14 mostly non-science teachers, the ENCs had a powerful impact on their thinking about the nature of effective pedagogy, we did not know whether some, all or any of the ENCs would have lasting power in influencing what teachers actually did in their classroom or the extent to which the ENCs were used to explain or rationalize classroom decisions. More formally, the current research question addressed how the ENCs influenced teachers' thinking and practices over time. To this end, a year after the course, we surveyed the same 14 teachers to assess their perceptions of the usefulness of the ENCs. Six of those teachers permitted classroom observations and participated in interviews that focused on how the ENCs influenced their teaching and classroom decisions.

We hypothesized that the ENCs would have an enduring role in influencing teachers' thinking or classroom decisions regarding their pedagogy, and that the ENCs would not dictate teacher pedagogy in any specific way. However, as in all qualitative work, we recognized that competing or rival hypotheses might also explain changes observed in teacher behavior or thinking (Yin, 2003). We explore these alternative hypotheses in the discussion section.

MATERIALS AND METHODS

Evaluating the long term impact of PD is a challenging endeavor, often relying on surveys, interviews and teacher self-reports (Garet et al., 2001; Penuel et al., 2007; Colbert et al., 2008; Ravhuhali et al., 2015). While observations are more challenging to organize and conduct, they also play a valuable role in evaluating PD (Guskey, 2002; King, 2014; Stecher et al., 2018; Tan and Amiel, 2019). Here we combine the advantages of surveys to provide the teachers' understanding of the perceived importance of ENCs in pedagogy, and classroom observations and interviews to describe the influence of the ENCs in teachers' pedagogical decision-making. We used a cross-case analysis of these teachers' interpretations and application of the ENCs to reveal if or how the ENCs influenced the teachers' practices.

Context

The study took place as a follow-up to a master's level course, Neuroscience for Educators, offered as an elective in a Mind Brain and Education program at a Midwestern university in May 2016. Details of the course were presented previously (Schwartz et al., 2019). Given that the teachers taught a variety of subjects across the entire K-12 spectrum, the course delivered content on the neurobiological basis of learning and memory using lessons appropriate for K-12 classrooms (MacNabb et al., 2006). Inquiry and active learning pedagogies were employed to model best teaching and PD practices (MacNabb et al., 2000; Garet et al., 2001; Desimone, 2011; Dubinsky et al., 2013; Darling-Hammond et al., 2017). Comparable neuroscience content and delivery have been evaluated as part of in-service science teacher PD (MacNabb et al., 2006; Roehrig et al., 2012; Dubinsky et al., 2013, 2019; Schwartz et al., 2019; Brick et al., 2021a,b). Briefly, the topics covered included general brain structures and their functions; neurons, synapses, and circuits; synaptic plasticity; autonomic nervous system and emotions; homeostasis; memory, learning and effects of drugs on brain function; social and emotional learning; epigenetics of learning and memory and nature vs. nurture; brain development; reading and circuit formation; ADHD and dyslexia. Approximately 20% of the course was lecture-based with the remainder utilizing active learning strategies such as questioning; discussions; modeling; dissections; short, independent station activities; and group guided and open inquiry that included data gathering, analysis, interpretation and communication. After each lesson, participants discussed the pedagogy demonstrated, how they learned the material, and how they might employ comparable pedagogy in their own practices. Participants were encouraged to make connections between the neuroscience and their teaching practices but such connections were not provided by instructors. Daily reflections captured what the neuroscience content meant to each participant. Lessons plans used in the course and demonstration videos from comparable PDs are available online (MacNabb et al., 2006). During the course, the ENCs (**Supplementary Table 1**) were not taught didactically but were used in assessments, so teachers did see them as a list of neuroscience concepts (Schwartz et al., 2019).

Participants

The study was formally approved by the Institutional Review Board of the University of Texas at Arlington. All 14 teachers who participated in the course voluntarily and formally consented to participate in a follow-up survey, 1 year after the course. All participants provided their written informed consent to participate in this study. Six teachers (**Table 1**) voluntarily consented in writing to be observed in their classrooms and interviewed afterward. Written consent or oral approval was obtained from school heads or administrators as dictated by district policies. Sample size was saturated, being limited by the initial course enrollment and the consenting process.

Data Collection

The data collection occurred late in the spring semester of 2017, toward the end of the academic year, approximately 11 to 12 months after the course. A mixed methods approach was employed to provide multiple data sources for gaining insights and forming conclusions. Thus, a survey, classroom observations and interviews have been utilized.

Survey

The survey probed the extent to which a teacher applied each of the ENCs in their practice on a scale of 0 to 100 (see **Supplementary Material**). For each ENC, teachers were asked to assess the degree of application in their pedagogy prior to taking the course, currently and in the future. By assessing perceptions at a single time point, the relative importance of the ENCs at present, past and future times can be more accurately judged and compared (Howard, 1980; Levinson et al., 1990). Any usefulness scale might drift over the course of a year if the survey had been administered in a pre-post design. With teachers' current knowledge of the ENCs and a year of using them, views regarding the ENCs would be expected to reflect their experiences both in and after the course. A response of 0 triggered the additional question: "If you are unlikely to apply this concept, what are the obstacles preventing its application?" The survey was administered digitally via Qualtrics. Aggregate survey data were returned to participants attending a reunion held at the end of the school year, where they verbally confirmed the findings.

Observations

For six teachers, a classroom observation was conducted to demonstrate how the influence of ENCs played out in real classroom contexts. Prior to the observation, each teacher filled out a two-question form, describing the lesson to be viewed and its place within the unit, and listing which ENC(s) influenced the lesson and why. The pre-observation forms were submitted via email before the classroom observations took place. The classroom observations were conducted at a time scheduled by the teacher. Many districts were worried that observations would disrupt classes and student learning, so only one visit was made per teacher. During the observation, the observer (VH), a former teacher, noted the sequential teacher dialog and actions. Teacher, and not student, behaviors were the focus of the observations. Copies of classroom artifacts were collected as needed to understand the observed lesson. The same observer carried out all classroom visits and interviews. Field notes were written (VH) for each teacher summarizing the classroom observation and the teacher's interview responses.

Interviews

Post-observation interviews were conducted with the six teachers to provide insight into how they thought the ENCs influenced their teaching practice. These took place outside of class at a time convenient to the teacher and observer, either immediately in person or within 24 h over the phone, following the observations. These structured interviews lasted 30 to 90 min. During interviews, teachers answered the same set

TABLE 1 | Teacher profiles.

Pseudonym	ENC used	Subjects Taught	Grade	Bilingual	FRL
Ms. Able	1, 4, 5, 8, 10	Language Arts	Pre-Kindergarten	No	69%
Mr. Ruiz	1, 2, 4, 5, 10	Math and Science	5	Yes	69%
Ms. Gomez	1, 2, 6, 9	Math	1	Yes	58%
Ms. Bell	1, 2, 3, 4, 5	Math	High school	No	1%
Ms. Crow	7, 8, 9, 10	Language Arts	4	No	69%
Ms. Lake	4, 5, 8, 10	Reading-Language Arts	K-5	No	39%

ENC used refers to ENCs the teachers noted in their pre-observation forms.
Bilingual, whether the teacher can provide instruction in both English and Spanish.
FRL, percentage of school population eligible for free or reduced price meals. Numbers were taken from school district websites. All other information was provided by the teachers.

of questions regarding each neuroconcept they identified (see **Supplementary Material**). In answering this set of questions, teachers identified actions they took during the observation and provided explanations for how they connected the ENC being discussed to those actions.

Quantitative/Statistical Analysis

The quantitative analysis was conducted on the survey data of all 14 teachers regarding the teachers' use of the 10 ENCs across the three time points. A two-way repeated measures ANOVA was conducted on the rating scores as the dependent variable with "time point" and ENCs as within-subject independent variables, using IBM SPSS® Statistics Version 26. Data from two teachers were discarded due to missing values. For all data analyses, the significance level was set at two-tailed $p < 0.05$. Pairwise comparisons using a Bonferroni correction were conducted as follow-up tests after significant effects were observed.

Cross Case Synthesis/Qualitative Analysis

To better understand how teaching decisions were influenced by the ENCs, we adopted the cross-case analysis approach (Stake, 1995; Baxter and Jack, 2008; Yin, 2017). Cross-case analysis permits finding commonalities across multiple teachers in different contexts that can contribute to generalizations about how relevant neuroscience knowledge can be applied to classroom practice (Miles and Huberman, 1994; Khan and VanWynsberghe, 2008). Furthermore, this kind of analysis can help "estimate the effect" of an intervention, such as the influence of ENCs on a teacher's pedagogy (Goertz and Mahoney, 2012, p.89). The coding and data analysis process followed a grounded theory approach (Creswell, 2013).

One author (VH) transcribed all the recorded interviews into written documents for access purposes and initially wrote individual summaries of each observation. Two authors (VH, JMD) reviewed and revised the summaries of individual cases. The summaries focused upon three components: (i) each ENC mentioned by the teacher, (ii) examples of teacher actions from the observations, and (iii) explanations of intentions provided from the interviews or pre-observation form. The purpose of this first pass analysis was to extract examples where specific ENCs were applied. A list of preliminary codes was formed from the research questions and the individual case summaries (ZC, JMD).

Following the formation of the preliminary codes, two authors (VH, MS) wrote 21 vignettes from the pre-observation forms, classroom observations, and post-observation interviews, illustrating instances in which the teachers indicated an ENC had some influence or application. The vignettes were discussed by all four authors and analyzed to refine the set of codes. Codes were sought that transcended the content of individual ENCs to address the application of ideas represented by one or more ENCs. Codes for specific pedagogical practices, e.g., working in groups, were considered lesson specific and were not likely to be universally encountered across single visits to each classroom. Evidence from interviews, observations and field notes was triangulated to identify common ways that the teachers applied ENCs, testing the set of codes. Codes were further refined, discussed, and tested iteratively by all authors until complete agreement was reached. Codes were initially considered saturated when all additional codes could be viewed as subsets of the existing set. Field notes were reviewed at this point as a check for completeness. Eight final codes emerged. Using the final list of codes, each author separately coded all the pre-observation forms, classroom observations, and the post-observation interview documents for each teacher on the ENCs they specified. Full agreement was initially achieved on 77% of the coding. Where disagreements occurred, examples were discussed, field notes were consulted and recoding continued until 100% agreement was reached. In addition, authors challenged each other to identify inconsistencies in the narratives, to find evidence that did not support the emerging themes, and to view teachers' use of ENCs from both explicit and implicit points of view. Notes were kept on each coding discussion and writing sessions.

Once coding was complete, we returned the qualitatively derived themes to the teachers and provided them with the opportunity to agree or disagree with their transcripts, the themes, and which themes their data supported. We invited teachers to engage with us further for follow-up interviews to gather additional feedback and data and waited a month for replies. We planned to use such conversations to help us find out what we might have misinterpreted or left out. All 5 responders agreed with the researchers' analysis but declined further interviews. The sixth teacher did not respond. While the reasons for this decline were not probed or volunteered, the added stresses of teaching during a pandemic may have contributed. Under these difficult circumstances, ethically, we did not feel that the time demands of our research agenda took precedence over teachers' main concern for student learning. Thus, without additional teacher cooperation, the synthesized member checking process outlined by Birt et al. (2016) was executed to the extent possible.

Final code saturation (Bowen, 2008; Sim et al., 2018) was confirmed when (1) all interview and observation data had been coded, (2) researchers repeatedly encountered the same insights from different participants across data sources, and (3) the coding results were confirmed by member checks (Creswell and Miller, 2000; Bowen, 2008), with no teachers adding new insights.

The codes were subsequently grouped into three themes explored in the next section. Theoretical saturation (Bowen, 2008) was reached when additional analysis could not reveal new themes. In writing the manuscript and choosing examples to illustrate the codes, the vignettes, observations, interviews and field notes were consulted. Quotes were taken from the interviews.

A number of procedures contributed to the validity of this process (Creswell and Miller, 2000). The teachers offered rich, detailed information regarding their own thoughts in how the ENCs influenced their practices which are conveyed below. From the perspective of the researchers, the extensive discussion and triangulation described above also examined the qualitative sources for disconfirming evidence. At various points in time, descriptions of the coding process and their justifications were written to provide an audit trail and the basis for this methods section. This constituted a form of journaling. Two authors (VH, ZC) were part of the original class (but were not observed), guaranteeing the teacher lens was represented collaboratively in the analysis and writing process. The views of a knowledgeable educational researcher (GR) were sought and manuscript drafts underwent two rounds of independent peer debriefing to assure that the identified codes were supported by the data.

A number of techniques were used to ensure the trustworthiness of this cross-case analysis (Lincoln and Guba, 1985; Erlandson et al., 1993). Relationships between investigators and teachers were prolonged, built over multiple years in the MBE program, the Neuroscience for Educators course, the survey and classroom follow-up, a reunion, and the ensuing member checking. Sample size was exhaustive being limited by course enrollment and administrative permission for observations. The purposeful investigation into classroom applications of the ENCs persisted for the maximum time permitted by administrations, providing observation and interview data for triangulation. Referential materials were collected when appropriate to understanding the observed classes. Member checking was employed to the extent teachers' remained engaged. The accuracy of the qualitative analysis was validated by peer debriefing. Internal documentation provided audit trails for the narrative descriptions of classroom events used in the qualitative analysis.

RESULTS

Survey

The survey probed the degree to which each ENC was applied in teachers' lesson planning, currently, retrospectively prior to taking the course and prospectively in the future (**Figure 1**). Mauchly's test indicated that the assumption of sphericity had not been violated for time [W (2) = 0.68, $p = 0.15$], or for ENC [W (44) = 0.001, $p = 0.17$]. Significant main effects were found for time [two-way ANOVA, F (2,22) = 12.26, MSE = 3798.64,

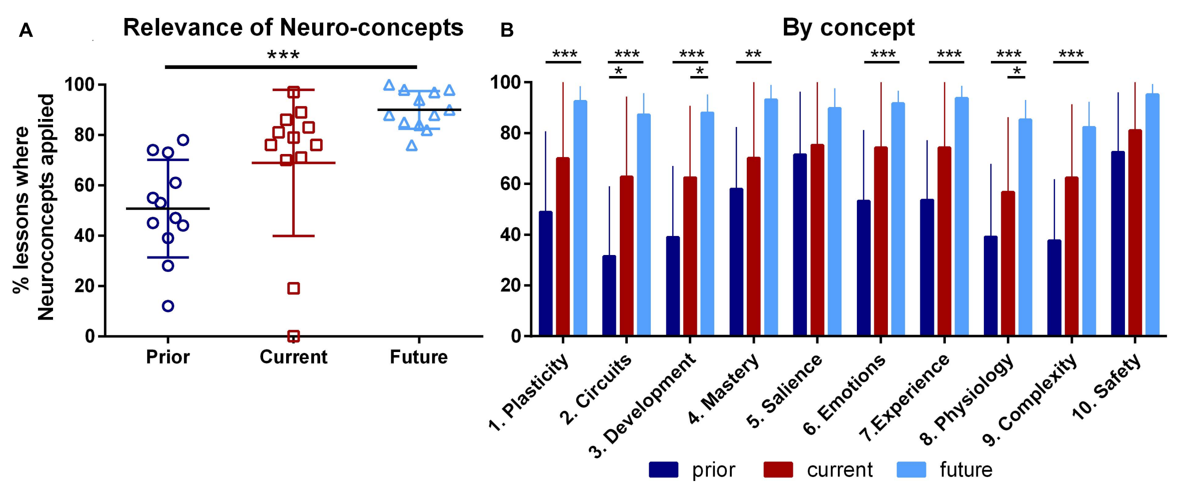

FIGURE 1 | Teachers ratings of the direct applicability of 10 neuroconcepts to their teaching prior to the Neuroscience for Educators course, in the current academic year and in future lessons. **(A)** Brackets represent mean ± SD for each time point. Individual data points represent different teachers, mean ± SD summed across all ENCs. The two lowest current responses were from teachers holding administrative positions, representing their limited exposure to students. Significance shown represents Bonferroni post-tests following the significant main effect of time ($p < 0.001$, Cohen's $d = 16.1$). **(B)** Bars represent mean ± SD for each individual ENC, summed across all teachers. Significance shown represents Bonferroni post-tests following individual one-way ANOVAs for each ENC (p-values < 0.001, 0.000, 0.000, 0.002, 0.14, 0.000, 0.001, 0.000, 0.000, and 0.054, respectively, for ENCs 1 to 10); *, **, *** represent $p < 0.05$, 0.01, 0.001, respectively; $N = 12$ teachers.

$p < .001$, partial $\eta^2 = 0.53$], for ENC [F (9,99) = 7.18, MSE = 333.01, $p < 0.001$, partial $\eta^2 = 0.40$] and for their interaction [F (18,198) = 3.78, MSE = 116.84, $p < 0.001$, partial $\eta^2 = 0.26$]. *Post-hoc* tests following the main effect of time indicated that there was an increase in the overall likelihood of applying the ENCs in teaching practice across the three time points, averaging over all 10 ENCs (**Figure 1A**). More specifically, teachers projected that they would utilize the ENCs in planning future lessons (M = 89.92%, SD = 6.6%) significantly more than their prior application (M = 50.56%, SD = 19.6%). When examining teacher responses by combining responses across all three time points, concept 10 had the most utility (M = 82.9%, SD = 11.6%) and concept 2 the least (M = 60.5%, SD = 17.8%).

Given the significant interaction, the effect of time on rating scores for each ENC was assessed (**Figure 1B**). Statistically significant increases in the perceived relevance between the retrospective prior and future estimates of use were found for all ENCs except 5 and 10. The estimates of prior use were consistent with the pre-intervention data previously reported (Schwartz et al., 2019). For ENCs 5 and 10, their greater relevance to teachers at prior and current times prevented significant increases due to ceiling effects. Significant increases were also observed between retrospective prior and current application for ENC 2, suggesting this idea was initially the least familiar to teachers. We also observed significant increases between the current application and future estimates of applicability of ENCs 3 and 8. Average current application of each concept exceeded 50%, indicating teachers generally found relevance in all concepts for lesson planning. In summary, although there was a general tendency for the use of all 10 ENCs to influence lesson planning to increase over time, the acceptance and application rate varied with each ENC.

Cross Case Qualitative Analysis

In planning the observed lessons and in the post-observation interviews, teachers discussed employing different ENCs. Teachers invoked 4 or 5 ENCs each, covering all ENCs. Among such a small sample, the frequency of ENC use cannot be generalized. Examples of how teachers applied each ENC, what was observed and how the teacher explained the connections appear in **Table 2**. The cross-case analysis looked beyond how individual ENCs were used (**Table 2**) and focused on identifying themes in the teacher observations and interviews that encompassed actions or thoughts across all ENCs. The overarching themes that emerged were the ideas that the ENCs influenced teachers' thinking about their pedagogy and their views of students, and teachers' planned and spontaneous actions in various classroom contexts (**Table 3**). The following discussion of examples supporting these themes includes the common idea that introduction of neuroscience ideas changed teachers' views or practice.

Theme 1: Teacher Thinking

ENCs affected teacher thoughts about pedagogical decisions

Across all cases, ENCs guided teachers' thinking about pedagogy. Teachers used the ENCs to reason why certain pedagogies were more effective, deepening their understanding of these approaches. For one teacher, this understanding illustrated how certain practices could be used. For another, the ENC affirmed or resolved prior concerns and doubts about specific practices.

Teachers thought about involving certain pedagogies in their lessons because ENCs helped them see why these pedagogies were effective. ENC 8 helped Ms. Able to acknowledge that students' physiology when entering the classroom, whether through hunger, lack of sleep, stress or emotional state, influences their learning capacity. This understanding led to pedagogical decisions that respected students' physiological and emotional needs. More specifically, in the observed lesson, Ms. Able welcomed each student upon their arrival and asked students to greet each other to "offset the problems they may bring from home." She also allowed students to play with Legos to "keep them calm and stress-free" while waiting for everyone to arrive. She added, "I knew it [taking care of students' emotional needs] was best for kids, but now I have a deeper understanding of why." Ms. Crow indicated that the course has a similar impact on her understanding of ENC 8, "I knew before it [ENC 8] was an issue, but after [the course] I knew why... I understand that those [nutrition, hormones, stress, and sleep] are factors within the child's learning." Considering the influence of physiological and emotional status on students' performance, Ms. Crow decided to be more patient in her interactions with them. In the observed lesson, a student was uncooperative. Ms. Crow's explanation reflected her consideration of the student's emotional needs, "To yell won't help, so I have to talk to him and be patient and calm. I give him alternative strategies to help him with behavior."

Educational neuroscience concepts also influenced teachers' thinking about how pedagogy should be used. In discussing ENC 1, Mr. Ruiz said, "The neuroscience class did influence my use of repetition. I am more aware how repetition should take place." He recognized that the student actions of repeating and remembering strengthened synapses as they learn. Mr. Ruiz told us that he used to focus repetition on mathematical algorithms but found that his students did not understand why they worked. In response, he repeatedly drew diagrams for students to copy, remember, and apply to later problems. He stated, "students are getting used to seeing me doing the exercises, the graphs and illustrations attached to descriptions of key words. They see a connection between what I say and how things actually work." In addition, during his math class, Mr. Ruiz instructed students to take notes, draw diagrams, and make personal observations in their personal notebooks. These actions gave students opportunities to repeat the exercise themselves in diverse ways, activating plasticity.

Educational neuroscience concepts also affirmed teachers' concerns about pedagogy. Regarding student engagement, Ms. Gomez pointed out, "We are so used to a toned-down delivery. The lessons aren't always experiential, and we are concerned with how we engage them [students]. Usually it requires an interesting activity or experience." She invoked ENC 6, justifying actively involving students in the observed lesson on fractions, "[The class] made it [ENC 6] more salient and gave me more of an incentive to use it on a daily basis... It is a lot harder to think about how you can create that [emotional] stamp... but I use at least one experience per unit or topic." Ms. Gomez

TABLE 2 | Examples of how teachers applied the educational neuroscience concepts.

ENC	Observed	Explanation	Change statement
1. Learning strengthens synapses. Remembering reactivates plasticity.	Ms. Able used a KWL chart to help students remember insect body parts.	I had never used the KWL chart before, but I used it specifically to help students to remember, so we went over it in the morning and when they left. I think my students used that chart and now they improved to a higher level than I expected.	I feel more confident. Before the class I knew [ENC 1] was important and after the class I wanted to make a greater effort to incorporate it into my lesson plan.
2. Different behaviors use different but overlapping circuits.	Ms. Bell gave students opportunities to wonder and investigate how to match graphs with correct equations.	Giving students the opportunity to look at the graphs, cut them out and key them into the graphing calculator and then place them with the correct equation was intentional to give them different experiences with the same concept.	The biggest difference is the confidence I have in it [ENC 2] being the correct approach. I am more intentional about using it.
3. Experiences and genetics shape circuit development.	The class used the Padlet app to compare graphs of different equations. Following Ms. Bell's instructions, students shared what they noticed, what questions they had, and what they thought about asymptotes.	I am surprised at how much progress can be made by those I least expected it from. It [ENC 3] has taught me not to judge who will respond and who won't.	
4. Rehearsal, application and self-evaluation lead to automaticity and mastery.	Ms. Able instructed students to use the information from the KWL chart to draw an insect and label parts. She asked students to talk about their drawings and the labels they wrote. When needed, she helped students sing the song to remember the body parts and transfer them to writing. She encouraged students to think about what they learned instead of just telling them answers.	I try to get students to apply what we're learning in different ways. . . . I use self-evaluation now, especially asking them what they think about what they're doing. I'll ask a 3 year-old to evaluate their work.	I used [ENC 4] less often before the class, and now I use it more often.
5. Salience and repetition strengthen synaptic and circuit development.	Ms. Lake provided a graphic organizer, "Somebody Wanted/But/So/Then," to help students remember the events of a narrative. She helped them read a story and then demonstrated on the board how to fill out the graphic organizer.	The plan was to repeat the lesson on [the] main idea and give them a visual [the organizer] that goes with it.	Now that I teach language arts, I realize the more important it is to use repetition - going back and evaluating what is going on and rereading the words, that sort of thing.
6. Emotions facilitate memory and decision-making.	Ms. Gomez gave students the opportunity to explore the concepts of equal and unequal by sharing a graham cracker with tablemates. The groups contained 1, 3, or 4 students. The groups were told to think of ways to share the cracker equally and draw their solutions. After breaking the cracker according to plans and observing the results in other groups, the students realized their pieces were not equally sized. After a discussion, students were given another chance. Results were better, but still some inequalities occurred because the sizes of the groups were different. Some students were frustrated or disappointed.	But I learned more about it [ENC 6]; made it [a] more salient idea and gave me more of an incentive to use it on a daily basis. We are so used to a toned-downed delivery. The lessons aren't always experiential. We are concerned about how we engage them [students]. Usually it requires an interesting activity or experience that can be carried on over a period of days.	I knew of it [ENC 6], but I learned more about it – to use it on a daily basis.

(Continued)

TABLE 2 | Continued

ENC	Observed	Explanation	Change statement
7. Brain pathways, while similar across individuals, are shaped by unique experience.	Ms. Crow reminded students that they had previously learned to use a Venn Diagram to compare and contrast using hula hoops. In this class, she reviewed 'compare and contrast' by drawing a Venn Diagram on the board and using hair color. Students were divided into 3 groups and each group read a different version of Cinderella. Using a jig-saw structure, students then were placed in mixed groups where each student read a different version. They were given large pieces of paper to draw the 3 circle Venn Diagram and compare/contrast the 3 versions. Groups posted their papers on the wall for a gallery walk and class evaluation.	I think about how students learn with their own experiences and that they are unique . . . and learn by doing.... I realize students need to start small and use sensory before they move into the representational level. Now we start at the bottom and build up.	I did it [experiential learning] differently before taking the class, but now I know more after taking the class. . . . It makes sense to me to start at the beginning, sensory-motor.... Earlier I never thought how important it was to begin at the lowest level.
8. Physiology influences learning, memory and decision making.	One student did not want to participate in the jigsaw reading group. Ms. Crow gently reminded this student to share ideas and participate in the group discussion.	The student who did not want to participate has emotional issues. To yell won't help, so I have to talk with him and be patient and calm. I give him alternative strategies to work on behavior. I try to be a role model for my students.	I knew [ENC 8] was an issue, but after [the class] I knew why. I have a lot more patience with my students because some are homeless or lack stable home lives.
9. Nervous system complexity produces reasoning, communication, creativity, curiosity.	At the beginning of the lesson, Ms. Gomez provided photos of whole items divided into parts with lines and items that had been physically separated into equal parts to help students see fractional relationships in both situations.	It [ENC 9] is what I tried to use at the beginning of the lesson. The pictures of each different item, one entire item and the one that had been sliced into pieces to see if they could organize/categorize the pictures. I want to step away and not tell them everything that is happening. I want them to tell me.	I used it [ENC 9] more after the class. I tie this concept to pattern recognition. I want students to come up with what's going on.
10. Safe learning environments provide opportunities for deeper learning.	One student was not engaged in the group activity. After a quiet reminder and no improvement, Ms. Crow asked the student to step into the hall away from the class to calmly encourage the student to add ideas to the group's Venn Diagram. She stood in the doorway while talking to the student so she could continue observing the other groups.	Every day I strive to create a safe learning environment with the student who didn't want to participate. He felt he couldn't participate because he didn't know what to do. It is challenging to create this safe classroom environment.	I've always known a safe learning environment impacted students and their learning, but I didn't realize why until after the class.

Statements teachers made with respect to each ENC, explaining their instructional choice and a change in their practices are also included. The explanation and change statement columns contain quotes from the interviews regarding the vignette in the observed column.

TABLE 3 | Cross-case comparison of how the teachers applied the ENCs.

Theme	Code	Ms. Able	Mr. Ruiz	Ms. Gomez	Ms. Bell	Ms. Crow	Ms. Lake
Teacher Thinking	ENC guided thinking about pedagogy.*	√	√	√	√	√	√
	ENC guided views of students.	√	√	√	√	√	√
Teacher Actions	ENC supported known practices.^	√			√	√	√
	Teachers tried a different approach.	√		√	√		
	ENC guided classroom actions.^^	√	√	√	√	√	√
Context of ENC use	Planning/Intellectual: planning a lesson or designing activities**	√		√	√	√	√
	Immediate/Management: reacting to immediate events when interacting with students	√				√	√
	Immediate/Pedagogy: during instruction or cognitive engagement of the class			√	√		

**This category includes evidence of the ENCs across a broad range of teachers' thoughts; justifications, deeper understanding, guidance, motivation, confidence, beliefs, etc.*
***This category focuses only on evidence for use of the ENCs in specific planning prior to the observed lesson.*
^This category includes evidence of teachers' reflections upon classroom practices they said they used previously. These practices may have been supported by an observation.
^^This category includes teacher narrative explanations which are consistent with the observations.

introduced the concepts of fraction using pictures of pizzas. She applied her deeper understanding to incentivize students with the opportunity to explore fractional parts using graham crackers and chocolate bars. Students realized the size of the portion was impacted by the number of students sharing the cracker. Students with the smaller portions were distraught; the outcome was unfair. These experiential activities provided students with rich emotional feelings that reinforced their memory of the lesson.

ENCs guided teachers' views of students

As the ENCs described and explained the fundamental neuroscientific processes in learners' brains, they enriched teachers' general understanding of students. This broader view embraced students' variability, unique backgrounds and capacities, and respected students' physiological and emotional needs. Thus, guided by the ENCs, teachers more intentionally incorporated these insights into their pedagogical thinking as they crafted students' learning experiences.

Educational neuroscience concept 7 helped Ms. Crow to appreciate that although learning the same content or skills would develop brain circuits for each student, the process may occur in unique ways. This idea further evolved into a new insight regarding different student learning progressions: "Students are unique. Some students don't need sensorimotor [activities], some need representational levels, and others need to work on the abstract level." Such a view of the students' learning process encouraged her to include activities that prepared students with more concrete experiences before transitioning to more abstract content. In her math lesson, Ms. Crow used actual hula hoops to help students understand the more abstract concept of Venn Diagrams, "I realize students need to start small and use sensory [activities] before they move to the representational level. Now we start at the bottom and build up."

Educational neuroscience concept 8 affected Ms. Lake's view of how physiological and emotional needs impact learning, "...[I] always felt the emotional status and the state the students are in make a huge impact on what they are doing. . . There is a bigger impact than we realize. . .nutrition, hormones, stress; all these factors affect the students." This view of students also led to a pedagogical decision in the observed lesson. At the beginning of class, a student was compelled to tell about a lightning strike in his neighborhood. Ms. Lake recognized his need to process and share that emotional event with his classmates, "If they are upset, they are not going to listen." Guided by this understanding, she let him finish the storytelling before starting with the lesson. Moreover, her awareness of the impact of safe learning environments extended beyond her classroom: "I knew that safe learning was important, but now I understand that it is essential to know when kids are being picked on in the halls. The effect on deep learning surprises me."

In addition, teachers noted their 'surprise' at the abilities of their students, after applying ENCs to practice. Teachers often hold an expectation of what their students are capable of, given their age, grade, and previous performance. Implementing pedagogies aligned with ENCs provided teachers an opportunity to see the potential of their students in a new light.

In discussing ENC 4, Ms. Able acknowledged that for her students to master what they were learning, they needed to constantly reinforce their synapses by approaching the material multiple ways, through rehearsal, application, and reflection. Thus, in her pedagogical plan of the lesson on insects, she aimed "to get students to apply what we're learning in different ways." She asked students to apply their knowledge of insects by singing, drawing and writing. She also asked them to discuss what they learned about the insects and reflect upon it. As a result of the practice, her view of her pre-K students changed, "It [pedagogy aligned with ENC 4] pushes them to higher level thinking. They are talking more and using vocabulary more often.... You ask a three-year-old to self-evaluate, and you don't think you'll get a good response, but they actually like it. . .they know if they have done their best. It is surprising in a good way."

The same occurred to Ms. Gomez, who obtained the idea from ENC 9 that learning should involve complex cognitive processes such as reasoning and communication. She associated this idea with a pedagogy with which she "want[s] students to come up with what's going on." and "verbalize what they think." Multiple times during the observation lesson, Ms. Gomez required students to turn to a partner to share their thinking. Then the students were asked to share with the class what they noticed from the activities in the lesson. Students' performance reshaped her idea of their ability, "Every time I use it [ENC 9], they surprise me with their answers - their ability to notice certain things. I think they won't notice this, but they do."

In a similar event, Ms. Bell noticed math anxiety in her students, and said, "Students come into this class believing they don't like math or can't do math. They don't have confidence and say, 'I'm not a math person.'" Guided by ENC 3, Ms. Bell embraced the idea that experience plays a pivotal role in learning. This idea strengthened her confidence in making her pedagogical decisions when addressing the math anxiety in her students, "There's an underlying idea that students need to be given complicated work, [but] I need to make the learning accessible so that they can have the experience that tells them they can do this." As a result of her effort, students in Ms. Bell's class impressed her with their potential, "I am surprised at how much progress can be made by those I least expect it from. It [The students' progress] has taught me not to judge who will respond and who won't."

Theme 2: Teacher Action. ENC Supported Known Practices, Encouraged Untried Approaches and Generally Guided Pedagogy

Beyond influencing teachers' views of students and thinking about pedagogy, the ENCs also influenced teachers' classroom actions. Intellectually, teachers connected the ENCs to pedagogical practices such as repetition [ENCs 1, 4 and 5], safe learning environments [ENCs 8 and 10], addressing students' emotional needs [ENCs 6, 8], providing students with agency [ENCs 1, 3–7, 9], and associating new learning to existing knowledge [ENCs 1–5, 7, 9]. They had learned about, knew of, and to some extent used most of these practices before taking the course. The course did not instruct teachers in the use of a set of "novel" practices. Instead, teachers made connections between the ENCs and the pedagogical practices modeled during the course. During classroom observations, the influence of the ENCs on teachers' pedagogical decisions were evident as teachers reflected upon their actions in the subsequent interviews. Teachers were observed to enact previously known pedagogies, and to try new or untried approaches. The ENCs generally guided sequences of teacher actions.

In a more pragmatic fashion, teachers invoked various ENCs in their use of pedagogies that were already familiar. Concerning ENC 4, Ms. Able indicated that having students apply their prior knowledge in learning new lessons and evaluate their progress was part of her practice, "I used it less often before the class and now I use it more often." Ms. Crow, related ENC 7 to matching activities to students at different stages of development, "I have done that before, like I've done differentiation where students discover their own learning." In similar fashion, Ms. Bell applied ENC 2, expressed that she had previously thought about integrating multiple different activities for students to learn about functions in her lesson, but had concerns about the investment of time for her set of activities. "The biggest difference is the confidence I have in it [now] being the correct approach." As for ENC 5, Ms. Lake told us that having students repeat what they have learned to improve memory has been a conventional practice for her, "I've worked with Special Ed for 15 years so it is not surprising. It is more science to go with the things that I have done. Like affirmation."

In other instances, teachers adopted previously untried approaches. Their understandings of why these pedagogies might be effective had been bolstered by the ENCs. Teachers were now confident that they could successfully utilize the novel pedagogies. For example, Ms. Able indicated that ENC 1 had motivated her to focus on the importance of helping students remember what they had learned, so she tried using a KWL chart. Ms. Able said, "I had never used the KWL chart before. I used it [chart] specifically to help students remember. My students used that chart, and they have improved to a higher level than I expected." Relating to ENC 9, Ms. Gomez knew that she wanted her students to express their own ideas because, in her own words, "the learning emerges from them." She added, "but it wasn't until I saw CRP [Critical Response Protocol – a strategy modeled in the course (Ellingson et al., 2016)]; that technique allowed me to see how I might use it [ENC 9] with my students." After the observed class, Ms. Gomez expressed her passion in utilizing this new approach, "I don't use it [CRP] just in math but also in reading and writing." Ms. Bell wanted her high school students to investigate the relationships between functions and graphs [ENC 2] so she devised an activity to physically sort and match the equations to the graphs. "The previous year, we gave them the equations and the graphs already graphed side by side. So they didn't get the chance to see all the graphs and wonder about them and investigate, 'what did they notice.' It was a more static and teacher-directed lesson."

More generally across all the interviews, teachers acknowledged at least one instance in which they applied an ENC as a principle to guide some aspect of their observed classroom actions. Ms. Lake recognized the importance of using repetition (ENC 4) when she kept reviewing the story line as she guided students to analyze and evaluate characters' motivations. Acknowledging the importance of having the students remember math strategies and procedures, Mr. Ruiz guided them in their note taking (ENC 5). Comparing the other teachers' observed actions and subsequent discussions revealed that different ENCs can lead to similar pedagogical choices and a single ENC can be applied in a variety of ways.

Ms. Bell and Ms. Gomez both chose to incorporate a sequence of experiential, student-centered activities in their lessons, but they attributed their pedagogical decisions to different ENCs. Ms. Bell gave high school students a more active role in exploring and interpreting the graphical shapes of rational functions through matching graphs with the respective equations and function tables and confirming their choices using a graphing calculator. Students then used a sticky note web app to share their observations, pose questions, and consider alternative points of view. She explained the influence of ENC 1 by saying, "I'm mindful that every new experience, idea, thought, changes the brain... so by making them experience the lesson, it opens up that plasticity." Ms. Gomez used ENC 6 to guide the actions she took to engage first graders and provide an emotional impact. During the observed lesson on equality and fractions, Ms. Gomez challenged the students to divide a single graham cracker equally among their three or four tablemates. After agreeing on a plan and then dividing the crackers, students rotated around the tables and realized that tables with three students had larger cracker pieces than those with four students. By the end of the lesson, students could explain the concept of equal and unequal using the varied sizes of cracker pieces in a more personal way than if Ms. Gomez had used paper cut-outs of fractional shapes. She stated, "The lessons aren't always experiential, and we are concerned with how we engage them [students]. It [engagement] requires an interesting activity or experience... it is a lot harder to create that stamp." Both Ms. Bell and Ms. Gomez invited students to share their thoughts and reflect on their learning with partners and the class. A common series of actions was seen in both teachers' classroom practice: reviewing prior knowledge (functions or concepts of equal and unequal), providing students with equipment (graphs or crackers), encouraging students to apply their prior knowledge in problem-solving (graphing a new function or splitting crackers equally), engaging students in various learning behaviors, inviting students to share their thoughts with partners or the class and encouraging students to evaluate and reflect on their learning. Although the activities are unique, both their actions focus on students in offering them a learning experience that "changes the brain (Ms. Bell)" and "creates that [emotional] stamp (Ms. Gomez)."

Both Ms. Able and Ms. Crow created environments where students felt safe physically and emotionally (ENC 10). Mrs. Able created a safe learning environment by going over the classroom rules daily, reminding the pre-K students to walk in the classroom, and leading students to think about why walking was a necessary rule. By understanding the importance of predictability in a young child's life, Ms. Able commented, "The schedule is consistent, and the rules are clear." In contrast, Ms. Crow organized her actions to respond to an individual fourth-grade student who was disengaged from the group he had been assigned to join. Initially, Ms. Crow whispered an encouragement to participate in the group activity. When the student became disruptive, instead of reprimanding him in front of his peers, the teacher quietly asked the student to step out into the hallway to better understand the reason for his reluctance to participate. In the privacy of the hall, the student shared that he did not know how to contribute to the group's assignment. She offered suggestions, and the student was able to return to the group without further issues. When asked about ENC 10, Ms. Crow indicated that until taking the course she did not understand how a safe learning environment impacted students and their learning. Now she considers it on a daily basis. In both cases, Ms. Able and Ms. Crow organized their actions according to their unique situations and ensured that students felt safe in their classroom physically and psychologically.

Theme 3: Context. Teachers Used ENCs to Respond in Different Contexts

The ENCs influenced teachers' practice across various educational contexts. For some teachers, the ENCs played a role when they were planning the lesson or designing activities. For others, teachers invoked ENCs in their decisions reacting to immediate events when interacting with students or guided teachers' immediate pedagogical decisions that deviated from the original lesson plan. Moreover, the ENCs guided the way teachers gave instructions or cognitively engaged the class. Immediate and contextual ENC uses were not as prominent as teacher thinking and actions.

Ms. Gomez and Ms. Able made it explicit in the interview that ENCs were influential when they were trying to decide on a pedagogy or activity. Ms. Gomez indicated that she invoked ENC 1 in her thinking, justifying why reviewing what students have previously learned was included in the lesson plan. "Depending on the subject... I try to attach the idea of prior knowledge in every lesson." When explaining her plans for the math lesson, she said, "We had learned about equality and inequality at the beginning of the year. One side has to equal the other side. Having them [students] remember that definition would help the synapses get stronger." Similarly, Ms. Able discussed using ENC 5 in planning to practice vocabulary, "I tried to plan for opportunities for them to repeat the vocabulary words like singing that song many times. That was one way to get them to repeat and practice... I definitely plan for those opportunities more often."

Sometimes the lessons did not unfold as teachers planned, when students were not engaged in the activities. Teachers need to react to these immediate classroom events, to manage the classroom appropriately or to shift gears and revise the lesson in real time to adjust to student needs. As described earlier, Ms. Able, Ms. Crow and Ms. Lake offered examples in which ENCs affected their immediate reactions to disruptive behavior. Ms. Able acknowledged the importance of maintaining a safe learning environment (ENC 10), preventing unwanted injury or chaos from running. Likewise, Ms. Crow was sensitive to a disruptive student's emotional needs (ENC 8), and provided him with a path forward. Ms. Lake also appreciated the emotional needs of students (ENC 8), and decided to let a student share with the class a lightning tale before transitioning to the lesson.

A third educational context in which teachers used ENCs to guide their thinking and actions was when they were trying to cognitively engage the class during instruction. This context was different from lesson planning because it did not happen before the class, but during the class. In lesson plans, teachers speculate on how their student would respond to the activity without knowing how they actually react. During the instruction, teachers need to quickly respond to students' reactions and help them to cognitively engage in the learning. In the during-instruction contexts, teachers need to be observant of subtle problems that may undermine students' learning experience and process. The ENCs also offered important insights into how teachers adjusted their pedagogy in this context. For example, over the course of the lesson matching functions to graphs, Ms. Bell wanted to have students share their thoughts to see what others observed using a sticky note app. Once she observed the way her students performed in that activity, Ms. Bell reoriented students' thinking to a deeper level by intentionally modifying the instruction, "That was another thing I changed, from 'I wonder if' to 'I noticed'. . . so students reflect on what other students saw and think about what they thought." This change was guided by ENC 4 that highlights the importance of self-evaluation to learning.

Overall, the ENCs affected the way that teachers selected pedagogy, organized lessons when planning the lesson, reacted to unpredicted immediate classroom events, and managed to maintain students' cognitive engagement in the class activity during instruction. We did not observe instances where the ENCs guided teachers responding to student misconceptions or terrific insights by spontaneously changing their pedagogy leading to a fruitful tangent.

Across all themes, teachers viewed the neuroscience ideas as applicable to their classroom decision making and practices in broad general terms. These ideas provided approaches, justifications, affirmations or resolutions to problems that arose in their classrooms. In the words of Ms. Gomez,

> *"It's [the ENCs are] all information we can use. It is hard for me to pick out one thing.... It all influences my teaching as a whole as it affects delivery.... It gives me a mental checklist to go through as I plan. One of the strongest impacts that learning about these nervous systems concepts have made are in accepting or rejecting certain teaching methods, practices, lesson delivery, . . . frameworks. Sometimes we are given mandates in how to deliver instruction, but now I find I have better ways to teach, and sometimes I ignore mandates that I know won't work. I say research shows that those activities aren't effective."*

Disconfirming Evidence

Across the six classroom observations, we found varying instances of the application of ENCs. Half of the teachers applied the ENCs liberally throughout their lessons. One teacher applied the ENCs a moderate amount in her observed class. Two teachers had many fewer classroom instances which were influenced by the ENCs. This could be attributable to many unexplored reasons, from lesson goals and content to available time. All teachers endorsed some use of the ENCs as guides to their practices during the interviews. In the summative interview responses, 4 of the 6 teachers stated explicitly that the ENCs were important to their teaching practices. The two teachers who did not respond this way were also the two teachers who had fewer classroom examples that they linked to an ENC. Rather than arguing forcefully that the ENCs did not apply, the more neutral endorsement by these two teachers may represent early stages of application.

DISCUSSION

Significant Findings

The survey and subsequent observations with interviews provided different perspectives on how the teachers viewed the ENCs. The surveys revealed that a year after PD, non-science teachers unanimously found the ENCs useful as organizing principles in their pedagogy. The observation-interview process demonstrated that the ENCs influenced teachers' views of students and informed their classroom pedagogy and actions. Collectively the ENCs may have contributed to what might constitute a neuroscience framework for approaching pedagogical decisions that allowed teachers to plan, act, think and respond in dynamic ways in and out of their classrooms.

The surveys demonstrated that teachers found some ENCs more useful than others. However, all were deemed relevant. All played an active role in the teachers' thinking about lesson design. Teachers indicated they were currently applying the ENCs and intended to continue to use them in the future as guiding principles. As the results represent the experiences of teachers of different ages, grade levels and subjects, the ENC's relevance appears to be stable over a year and useful in a variety of educational contexts.

Classroom observations and interviews offered a more nuanced view of how the ENCs impacted participant thinking and actions. Three themes summarized how the ENCs influenced teachers' (1) thoughts about pedagogy and students; (2) actions in planning and execution of lessons; and (3) responses to events in and out of the classroom. These themes highlighted the principal ways in which the ENCs influenced teachers' pedagogical decisions in real time as well as in lesson planning.

Like other theories provided by developmental psychologists that act as frameworks (Beloglovsky and Daly, 2015), the ENCs provided a rational basis for making pedagogical decisions. Thus we consider that they may act as a framework for exploring pedagogy. We did not examine whether the ideas provided in the ENCs replaced or competed with other more traditional educational theories. The ENCs should complement rather than supplant prior theories by providing the biological basis for educational psychological findings (Diamond and Amso, 2008). The ENCs were designed to summarize important neuroscience concepts that teachers should understand (Dubinsky et al., 2013). They were not designed to describe developmental progressions or behavioral interventions. Teacher responses in the current analysis support the idea that the ENCs may be useful as a set of guidelines, or framework, for making pedagogical decisions both in planning and real time.

The Role of ENCs in Teacher Pedagogy

The three themes emerged through the teachers' use of a number of different ENCs, providing them agency and insight (**Table 3**). The first theme, Teacher Thinking, was illustrated through two perspectives: the teachers' current or updated thoughts about their pedagogy or their views of students. Noteworthy, this was the only theme where the ENCs influenced all six teachers through both perspectives. The second theme, Action, characterized how the ENCs influenced teachers' classroom practices through supporting known pedagogies, encouraging them to try new pedagogies and generally guiding sequencing or pedagogical choices. Teachers took the ENCs into account as they prepared, organized, or sequenced activities prior to encountering students (**Table 3**). All six teachers identified ways that the ENCs supported or guided their classroom actions. Four of the six teachers specifically pointed out how the ENCs supported practices they considered using or were encouraged to continue using. Half of the teachers claimed they tried a different approach because the ENCs justified the change. Again, all teachers used one or more ENCs as the basis for a specific action or change they made. The third theme, Context of ENC Use, reflected how ENCs were applied in lesson planning or how they helped teachers respond to emerging classroom issues. Multiple examples across five of the six teachers highlighted situations where their thoughts about pedagogy were directly supported by observed responses to specific management issues or the need to make instructional changes while engaging with students. The flexibility and power of the neuroscience framework emerged from the unique ways that teachers applied the ENCs in real time to behavioral or pedagogical challenges (**Table 3**).

The teachers used the ENCs to guide their classroom actions as well as respond to student needs. The observations and interviews revealed how teachers invoked various ENCs to justify new pedagogical approaches, classroom goals and methods. Teachers demonstrated insight into the nature of student problems and how to increase student agency. They used the ENCs to justify changes in lesson plans and strategically choose pedagogies, as Ms. Gomez noted, "Sometimes we are given mandates in how to deliver instruction, but now I find I have better ways to teach." The ENCs contributed to a framework that helped teachers explain student behaviors and understand the impact of students' emotions on learning and development. While the ENCs were not prescriptive in terms of dictating specific actions, they helped teachers organize actions in response to specific contexts.

Additionally, we cannot claim that this set of ENCs is the most parsimonious in generating similar results. The current set of ENCs were honed through multiple experiences to provide a foundation for teacher PD (Dubinsky et al., 2013, 2019). Neuroscience topics and activities that did not deepen the understanding of learning and memory (for example sensory transduction) were removed from iterations of similar neuroscience teacher PD (MacNabb et al., 2006; Roehrig et al., 2012). Some ENCs resonated more with teachers than others. Unpacking the relevance of any particular ENC to the overall framework may be possible in future research. A more nuanced view proposes teachers are not responding to the framework as a whole, but rather to individual ENCs that resonate with them. However, across this diverse group of non-science teachers, we observed no one-to-one correspondence between ENCs and specific pedagogies. Rather, the teachers used the ENCs to guide a broad range of classroom actions.

Collectively the ENCs represented a body of foundational understanding about the brain that increased teacher agency. Teachers made their own connections or translations between the ENCs and their own practices. They shifted their focus from the lesson, classroom management and organization to the students' needs, issues and success. Teachers recognized the importance of the students' experiences and desire to be agents of their own learning. This shift was revealed when the teachers discussed and synthesized how neuroscience might impact their practices rather than having the ENCs prescribe specific classroom actions. Evident among all teachers was the neurological basis underpinning their understanding of student behaviors, needs, emotions and states of mind. Comparably, elementary teachers who participated in a 2-year lesson study program framed by neuroscience theories deepened their understanding of student knowledge construction and could justify their pedagogical decisions through a neuroscience lens (Tan and Amiel, 2019; Tan et al., 2019). After a course in neuroscience, Israeli teachers similarly embraced neuroscientific justifications for pedagogical choices and increased their support of individual students' needs (Friedman et al., 2019). In their final comments, the interviewed teachers emphasized the influence of the ENCs as a frame for viewing student learning, growth and progress, and how to integrate views of students with effective pedagogy. As Ms. Bell noted, lesson plans not only need to address, "...all the elements in a lesson plan" but "...what is important from the standpoint of the students." Viewed more systematically, Ms. Crow emphasized that "policy makers need to know about the brain and how students learn. . . . Sometimes teachers are not flexible and teach the same way they've always taught." Thus, foundational neuroscience knowledge acted as a framework to help teachers develop both their pedagogy and views of students.

Rival Hypotheses

Unlike experimental designs, the case study cannot rule out all alternate explanations, yet plausible competing hypotheses can still be addressed to increase the certainty of conclusions (Yin, 2011). Study limitations are also considered along with the alternative hypotheses. The prerequisites of having attended the course and consenting to be observed limited the sample size. Since the teachers taught in diverse settings, the six cases compared here are in line with the recommendation for 6–10 cases for a purposive cross-case analysis (Malterud et al., 2016). The small sample size of this case study and its lack of controls prevented generalization of the findings. However, we can rule out the null hypothesis that the ENCs, as a framework, had no lasting impact on teachers' pedagogy. The survey results clearly demonstrated the relevance and importance of the ENCs to teachers a year later, which are confirmed in interviews. All teachers highlighted the impact of the ENCs in their thinking, actions, and sensitivity to their students' learning needs. Teachers embraced and internalized a deep understanding of how learning takes place. As one teacher expressed, "I really owned it [synaptic plasticity] after taking the Neuroscience of Educators Class."

Threats to validity of the study include selection bias, context and interactions between the teachers and researchers. The teachers self-selected in choosing to attend the Neuroscience for Educators course and the MBE program. Thus, they were predisposed to want to learn neuroscience. While we observed that this diverse group of non-science teachers all used the ENCs to guide their classroom actions, whether the ENCs can act as a framework for all teachers is unclear. Furthermore, context matters (Fischer and Bidell, 2006). Teachers who are struggling, facing shortages of resources or absence of support may view the ENCs differently than teachers who are currently satisfied with their instruction methods, have all the resources and support they want and generally enjoy their students and their jobs. To understand the impact of the ENCs in teacher training better, we recommend that future research focus on larger samples, in diverse contexts with teachers who are not self-selected, as in this study. Although there is a consistent trend that neuroscience knowledge positively influences teacher pedagogy across different countries with both pre- and in- service teachers (Tan and Amiel, 2019; Tan et al., 2019; Howard-Jones et al., 2020; Luzzatto and Rusu, 2020; Brick et al., 2021a,b), we can't comment on how well the ENCs serve teachers who are currently satisfied with their approach to teaching and their work environment. Lastly, interactions between the teachers and the researchers who were embedded in the research as instructors could have influenced the outcomes. Teachers might want to please instructors. However, the teachers were generally very open and honest about where and when experiences did or did not resonate with their thinking and practice. The amount of ENC application varied among the teachers (**Table 3**). In regard to ENC 3, Ms. Bell said, "Honestly I'm not following the meaning of #3." If an ENC felt redundant to previous training, teachers also told us. Referring to ENC 5, Ms. Lake did not inflate the importance of the ENCs saying, "I've worked with Special Ed for 15 years so it [ENC 5] is not surprising. . . It is more science to go with the things [teaching strategies] I have done. . . like affirmation."

One competing hypothesis may be that the ENC framework only confirms what educational researchers have already demonstrated as best teaching practices. But that conclusion may be too categorical given that all the teachers interviewed claimed that their views of students had changed as a result of the neuroscience training. Furthermore, the teachers discussed their interest in understanding the reasoning behind the need to implement best practices. The ENCs provided explanations that teachers used to justify implementation of certain strategies or choice of one strategy over another. Owens and Tanner (2017) provide a detailed description of how neuroscience can explain the efficacy of the think-pair-share strategy. Similarly, the ENCs provided the current teachers with a neurobiological explanation for why best practices work.

A second alternative hypothesis would be that the active learning incorporated into the PD experience produced the changes in teachers' practices, rather than the neuroscience content. In this case, teacher justifications should have been that they liked what they experienced and were trying to imitate that. The pedagogy used in the PD was consistent with best PD practices (Garet et al., 2001; Desimone, 2011; Darling-Hammond et al., 2017). We further argue that the nature of the pedagogy used to present the ENCs should be consistent with the ENCs. Resolving this issue would require further controls examining what specific influence the pedagogy used in the PD has on classroom implementations, as opposed to the neuroscience content.

The third alternative hypothesis is that previous training may be playing decisive roles in the observed changes. These teachers were currently or had previously enrolled in other courses in their master's program or may have experienced other PD elsewhere. Such experiences were expected to be diverse but could have contributed to their individual process of change. Several teachers did mention how ideas from their master's program resonated with this course. Such overlapping experiences are consistent with the possibility that teachers are continuing to integrate their understanding of how students learn and that the outcomes observed here are related to the program more than to a single course. Only a stand-alone PD experience could rule out any overlap; yet in the great majority of cases, teachers consistently used neuroscience to justify, explain or apply a practice with what they claimed was deeper understanding, more motivation or greater confidence. In a similar fashion, only a control group could allow us to rule out if the natural growth of teachers responding daily to the needs of their students would have brought them to the same conclusions they reached after this course. Thus, the boundaries are fuzzy that distinguish where experiences are unique and account for the reported observations vs. when they are complementary and resonate, leading to further growth.

Current Thinking and Discourse

Feiler and Stabio (2018) characterized the relationship between neuroscience and education over the last three decades as proceeding along three themes: application, collaboration or translation. Where the effort focused on the application of neuroscience to education, the goal was to find ways to directly inform practice based on neuroscience findings. However, the responsibility for this effort has created issues of agency. When researchers assume the responsibility, we characterize the effort as "researcher-initiated." Han et al. (2019) model this approach by assembling interdisciplinary research teams representing multiple perspectives to find where and how neuroscience can inform educators. In contrast, when the responsibility shifts to teachers for finding applications, we characterize this effort as "teacher-initiated," which increases their agency. In general, we expect that application research will continue to offer insights on how the brain supports academic behavior in areas such as math, reading or executive control (Bunge et al., 2002; Gabrieli, 2009; Lyons and Beilock, 2012; McNorgan, 2021); but whether researchers or teachers are responsible for finding ways to apply insights to education will impact teacher agency. Alternatively, collaborative relationships (Feiler and Stabio, 2018) seek a more even contribution from educators and researchers where all parties collaboratively define and address challenges of interest. This arrangement assumes that the outcomes are greater than that from any individual contribution. This approach has inspired the creation of research school networks or models of collaboration similar to hospitals preparing interns with the goal of providing teachers the necessary time, experience and practice to build personal meaning out of complex ideas so that they can use them responsibly and meaningfully (Fischer, 2009; Schwartz and Gerlach, 2011). Ultimately graduates of such programs are highly skilled in research methodologies, the epistemologies of different disciplines as well as the content each discipline generates. While some graduates return to the classroom to leverage these skills, others are recognized as experts in their school districts or their communities. They are emerging as a new class of professionals, neuro-educators, skilled at scaffolding or mediating conversations to define the value, purpose or potential in new neuroscience research (Schwartz and Gerlach, 2011). In this regard, these neuro-educators can act as agents in supporting Feiler and Stabio (2018)'s last theme, translation, where the goal is to make neuroscience research more accessible to educators to improve teaching and learning. However, this theme transfers the responsibility of understanding and applying neuroscience concepts to the classroom from researchers to a new class of experts, which has the same effect of undermining teacher agency.

Fitting between these tiers is PD that focuses on increasing teacher agency by providing relevant neuroscience knowledge to education, as explored here. While the time commitment is shorter than the collaborative efforts described earlier by Feiler and Stabio (2018), this PD must still ensure that the neuroscience is accurate and not misconstrued, and provides teachers the time to develop a personal understanding of relevant neuroscience concepts so they can identify their value in their own contexts (Dubinsky et al., 2013; Tan and Amiel, 2019; Tan et al., 2019). To explore the feasibility of the teacher-initiated approach, we provided teachers with neuroscience knowledge and the opportunity to discuss its connection and application to their practices. Then we followed-up with them after a year of teaching to explore their thinking about the relevance of a set of foundational neuroscience concepts (the ENCs) to their practices. The teachers applied the neuroscience ideas in diverse ways to their planning and classroom implementation of lessons, reinforcing known or encouraging untried pedagogies in a variety of contexts. While neuroscience did not dictate specific practices, it provided teachers with a knowledge basis for making pedagogical choices, in advance or on the spot in class. In this way, the ENCs may have acted as a framework for evaluating and understanding what constituted best classroom methodologies.

Shulman outlined seven different kinds of knowledge that teachers needed in their profession: content knowledge, general pedagogical knowledge, pedagogical content knowledge, theoretical knowledge of educational philosophies/theories, knowledge of the curriculum, knowledge of educational systems, and knowledge of students (Shulman, 1987). Researchers who otherwise argue appropriately for which neuroscience concepts are relevant to education may overgeneralize when they assert that neuroscience directly impacts pedagogical knowledge (Ansari et al., 2017). They forget that educational research, not neuroscience research, determines best classroom practices. Neuroscience provides the foundational knowledge of what goes on in the brain as one learns. This falls clearly into Shulman's category of knowledge of students, which included their physiology and development (Shulman, 1987). In the current study, teachers also conveyed that neuroscience changed how they viewed their students, indicating a growth in their knowledge of students. Teachers utilized this (neuroscience) knowledge of students to choose appropriate pedagogies, whether content specific or general, from their own pedagogical knowledge. Neuroscience may have provided a framework upon which the teachers could prioritize and make appropriate pedagogical decisions. Thus, neuroscience supplied teachers with usable knowledge that they could apply in their practices. These results satisfy Clement and Lovat (2012)'s criteria establishing the relevance of neuroscience to education.

DATA AVAILABILITY STATEMENT

The raw data supporting the conclusion of this article will be made available by the authors, without undue reservation.

ETHICS STATEMENT

The studies involving human participants were reviewed and approved by the IRB of the University of Texas at Arlington. The patients/participants provided their written informed consent to participate in this study. Written informed consent was obtained from the individual(s) for the publication of any potentially identifiable images or data included in this article.

AUTHOR CONTRIBUTIONS

MS, JD, VH, and ZC contributed to conception and design of the study, performed the qualitative and cross-case analysis, interpreted the results, contributed to manuscript drafting and editing, read, and approved the submitted version. JD and VH conducted the course, collected the data, and transcribed interview and observation data. ZC performed the statistical analysis on the survey data. All authors contributed to the article and approved the submitted version.

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SUPPLEMENTARY MATERIAL

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Advancing Neurolinguistics in Russia: Experience and Implications of Building Experimental Research and Evidence-Based Practices

Maria V. Ivanova[1,2]*, *Svetlana Malyutina*[2] and *Olga Dragoy*[2,3]

[1] Aphasia Recovery Lab, Department of Psychology, University of California, Berkley, Berkley, CA, United States, [2] Center for Language and Brain, HSE University, Moscow, Russia, [3] Department of Experimental Study of Speech, Institute of Linguistics, Russian Academy of Sciences, Moscow, Russia

Russia has rich theoretical and behavioral research traditions in neurolinguistics and neuropsychology, but at the beginning of the twenty-first century contemporary experimental research in these disciplines remained limited, leading to proliferation of non-evidence-based approaches in education, healthcare, and public beliefs. An academic response to this was the establishment of the Center for Language and Brain at the HSE University, Moscow, which focused on experimental psycho- and neurolinguistic research and related evidence-based practices. The Center has grown from a small group of young researchers to a large interdisciplinary unit that conducts cutting-edge research utilizing multi-site settings and novel structural and functional neuroimaging methods. The overarching aim of the Center's research is to promote scientifically grounded treatment of the language-brain relationship in the educational, clinical, and industry settings. Specifically, translational research at the Center is contributing to the advancement of clinical practice in Russia: from providing the first standardized aphasia language test to implementing protocols for intraoperative language mapping in neurosurgery departments across the country. Within research projects, a new generation of scientists is successfully being fostered, while a broader student audience is reached via courses taught by staff of the Center to students of different majors. Notable examples of public outreach programs at the Center are the Annual Summer Neurolinguistics School attracting hundreds of attendees from different countries each year, and community projects focused on raising awareness about aphasia. Together, these efforts aim to increase scientific knowledge in a multi-professional audience. In this paper, we will share our joint experiences in establishing, building, and promoting a neurolinguistics research center in Russia and the impact that this work has had on the broader public. We will delineate specific milestones of this journey and focus on the main pillars that have contributed to our progress: research, clinical work, teaching, and public outreach programs. We hope that this critical appraisal of our experiences can serve simultaneously as an inspiration and a practical guide for other groups developing research, clinical, and educational programs in different neuroscientific disciplines across the globe and aiming to improve the quality of the neuroscientific information available to the public.

Keywords: neuroscience, neurolinguistics, aphasia, education, public outreach, program development

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Analía Arévalo,
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Lívia Ivaskó,
University of Szeged, Hungary

****Correspondence:***
Maria V. Ivanova
ivanova@berkeley.edu

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INTRODUCTION

Russia has rich theoretical and behavioral research traditions in linguistics, starting in the late nineteenth and early twentieth century with the works of, among others, Ivan Baudouin de Courtenay and Lev Shcherba, and continuing with pioneering studies in structural linguistics by Roman Jakobson and more contemporary works in psycholinguistics by Revekka Frumkina, Alexey Leontiev, Stella Tseitlin, Tatiana Chernigovskaya and many others (Berezin, 1984; Alpatov, 2005). Similarly, the Russian neuropsychology school formed by Alexander Luria in the middle of the twentieth century has been very prolific in clinical research (Luria, 1980) and influential within and outside of Russia (Tupper, 1999). Despite this heritage, research in psycho- and neurolinguistics in the beginning of the twenty-first century remained fragmented and often only qualitative (for a critical review, see Fedorova, 2020). Only scattered studies have employed sound empirical methods for behavioral psycholinguistic research (e.g., Fedorova, 2009) or for further elaborating Luria's theory of higher cortical functions (e.g., Homskaya and Moskvin, 2000; Akhutina, 2002). The lack of a systematic scientific approach and a strong experimental school that would include neuroscience methods inevitably led to proliferation of non-evidence-based approaches in education, healthcare, and public beliefs.

In 2009–2010, a small initiative group of young researchers with backgrounds in linguistics, speech-language pathology, and neuropsychology began a series of behavioral studies into language and memory, followed by application for independent funding to Russian research agencies. These investigations served as the foundation for the Neurolinguistics Laboratory, co-founded by Dr. Olga Dragoy and Dr. Maria Ivanova 3 years later at the HSE University in the framework of the HSE Basic Research Program. In 2014, with additional funding from the HSE University as a part of the Russian Academic Excellence Project 5-100, it became the International Neurolinguistics Laboratory headed by Dr. Olga Dragoy and co-headed by Dr. Maria Ivanova with guidance from a senior scientist and a prominent figure in the field, Prof. Nina F. Dronkers (University of California Berkley, U.S.), who took on the role of the scientific advisor for the laboratory during its first 3 years. Incrementally, through collaborations with numerous leading international scientists, the diverse empirical behavioral inquiries broadened to include many cutting-edge neuroimaging methods: from lesion-symptom mapping approaches to electrocorticography. For the next stage of development, the laboratory was able to receive the prestigious mega-grant from the Russian Government in 2017. In 2018, with that funding under the leadership of Dr. Olga Dragoy and co-headed by Dr. Svetlana Malyutina with the distinguished neurolinguist Prof. Roelien Bastiaanse (University of Groningen, the Netherlands) as the scientific advisor, the Center for Language and Brain was founded on the basis of the Neurolinguistics Laboratory. In addition to these larger sources of funding to support the main research program, the team has obtained numerous smaller grants from public agencies (Russian Foundation for Humanities, Russian Foundation for Basic Research, Russian Science Foundation) for individual and exploratory projects. Today, a wide range of research projects on cognitive and neural mechanisms of language and related cognitive functions in diverse typical and atypical populations are conducted at the Center. The overarching aim of the Center's continuously expanding research program is to promote scientifically grounded treatment of the language-brain relationship in the educational, clinical, and industry settings. The main milestones and highlights of this decade-long (and still continuing) journey are presented on a timeline in **Figure 1**.

In this paper, we will share our joint experiences in establishing, building, and promoting a neurolinguistics research center in Russia and the impact of this work on the broader community. We will delineate specific milestones of this journey and focus on the four main pillars that have contributed to our progress: research, clinical work, teaching, and public outreach programs. We will discuss distinct actions that have been particularly effective and pitfalls that we encountered along the way. We hope that this appraisal of our experiences can serve simultaneously as an inspiration and a practical guide for other groups developing research, clinical, and educational programs in different neuroscientific disciplines across the globe and aiming to improve the quality of the neuroscientific information available to the public.

RESEARCH ADVANCEMENTS

Research was the starting point in the development of the Neurolinguistics Laboratory and to this day remains the main driving force of the Center's growth, uniting other areas of service and activity, such as clinical, teaching, and public outreach work.

A decade ago, the research began with behavioral psycholinguistic studies in healthy participants and individuals with post-stroke aphasia. The authors of this paper along with several other junior researchers and students at first used behavioral methods alongside eye tracking to explore the cognitive and linguistic mechanisms supporting sentence comprehension. A collaboration with the Center for Speech Pathology and Neurorehabilitation in Moscow (which would later become the Center's prime clinical partner on numerous projects) enabled us to access the population of patients with neurogenic communication disorders after stroke and to use the Center's eye tracking system for experimental research. This series of behavioral experiments laid the groundwork for programmatic research on linguistic and cognitive mechanisms of typical and atypical language processing. The use of eye movement measures in addition to offline behavioral methods allowed to keep up with modern trends in psycholinguistics, where particular emphasis is placed on understanding online language processing. These investigations offered insights into the contribution of different memory and attention processes in healthy participants and individuals with neurogenic language disorders (Laurinavichyute et al., 2014; Ivanova et al., 2015). The first studies and subsequent publications were critical in establishing the group's scientific competencies and helped to obtain subsequent funding. Additionally, these first

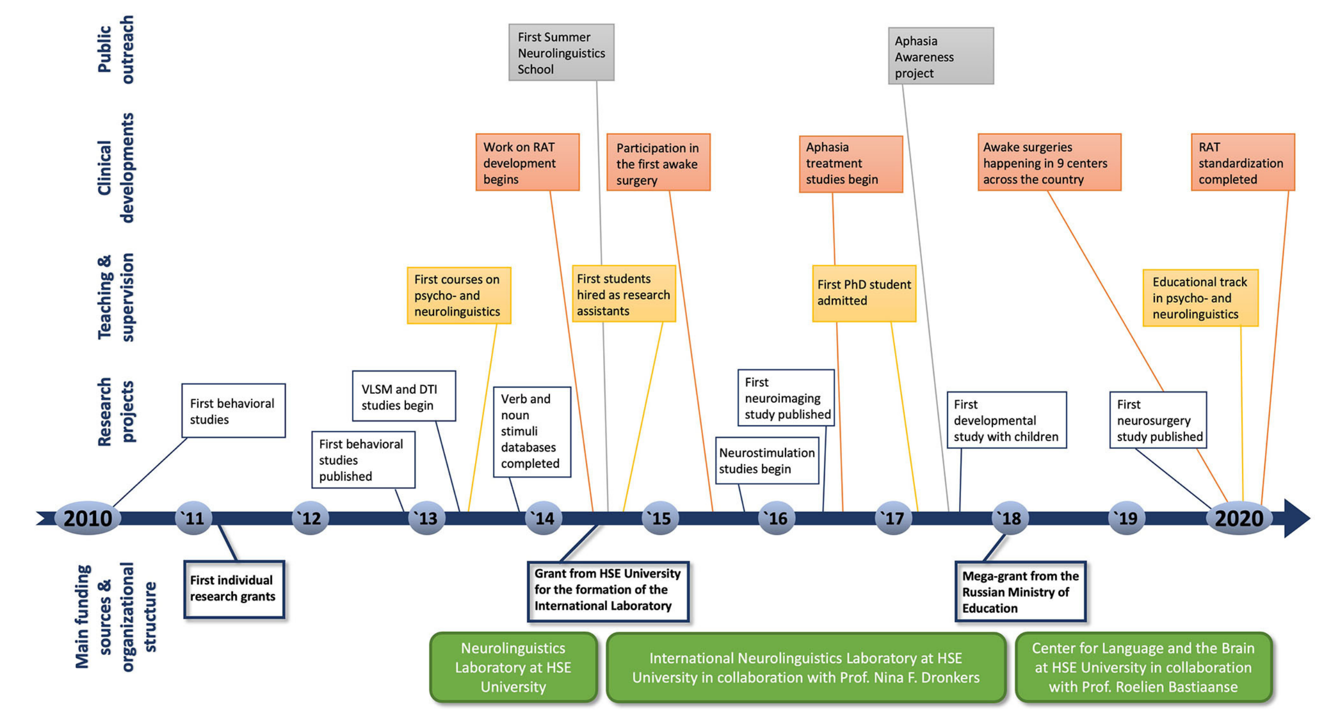

FIGURE 1 | Timeline representing the advancements and contributions made by our team to the field of neurolinguistics in Russia in 2010–2020, highlighting the main milestones and accomplishments in research, clinical work, teaching and supervision, and public outreach programs.

investigations solidified the first clinical collaborations that would be vital for further development.

At the same time, our team realized that in order to establish a strong research program in psycho and neurolinguistics, a sound foundation was needed: a database of experimental stimuli with established and validated properties. Compared to English and other European languages, Russian lacked publicly available databases of word properties beyond lexical frequency. To fulfill this gap, work on verb and noun databases began. Our group normed an extensive list of verbs and nouns by collecting data on relevant psycholinguistic word properties (age of acquisition, imageability, and image agreement) along with parameters of corresponding visual stimuli (name agreement, action/object familiarity, and subjective image complexity) through online questionnaires (Akinina et al., 2014, 2015). This allowed to create a psycholinguistic database of stimuli that served as a solid foundation for future research and clinical work. For instance, the assessment instruments developed by our group (such as the Russian Aphasia Test—see next section for more details) are largely based on stimuli from these databases. Many of our subsequent experiments rely on these stimuli as well (e.g., Yurchenko et al., 2017; Soloukhina and Ivanova, 2018; Malyutina and Zelenkova, 2020). In other words, without this groundwork of creating a database of stimuli, the next set of projects would not be possible. The databases have been made publicly available (http://en.stim-database.ru/) and are also being used by other research groups studying the Russian language. Moreover, a database in the Tatar language, the second most common language in Russia, has been created (http://stim-database.ru/ru-tatar/). Together, these efforts laid the foundation for quantitative psycho- and neurolinguistic research in the Russian-speaking population.

Our first steps in experimental psycholinguistic research were inevitably related to the specific properties of the language we dealt with—Russian. Most contemporary psycho- and neurolinguistic models rely on English and at best take into account some other Indo-European Germanic or Roman languages (e.g., Dutch, German, Spanish). In contrast to them, Russian as a representative of Slavic languages, has by far a more developed morphosyntactic system: three genders, six cases, at least three traditionally distinguished declension types and two conjugation types, lexical-grammatical aspect, agreement in case, gender and number, complex system of morphonological alternations, and free word order. On one hand, these differences made it challenging to directly adopt Anglocentric models to a wide range of linguistic phenomena. But on the other hand, these disparities afforded numerous opportunities for more careful testing and further exploration of existing psycholinguistic models. One such example is our eye-tracking experiment that allowed to reinterpret filler reactivation at the trace position in wh-questions, due to the use of specific constructions existing in Russian, but not in English (Sekerina et al., 2019). In another study, free word order and case marking in Russian allowed us to comprehensively test the impact of isomorphism as a linear agreement between the order of sentence constituents and the temporal sequence of events on sentence processing (Dragoy et al., 2016b; Chrabaszcz et al., in press). Thus, overall, specific features of experimentally understudied languages enable to refine existing linguistic models and afford new generalizations about language processing. The integration of such a language into the global research agenda might not be easy in the beginning but is ultimately rewarding.

After successfully completing several behavioral and eye tracking projects and having developed a stimuli database, we felt ready to start tackling the least addressed area in Russian experimental linguistic research—the neural mechanisms underpinning cognitive and linguistic processes. This required becoming proficient at using neuroimaging methods and collaborating with institutions that had this research infrastructure. Here, partnerships with clinical sites established while conducting our first behavioral and eye tracking experiments enabled us to access MRI scanners and EEG systems at these facilities. We began mastering fMRI and ERP methods by collaborating with mentors in Germany (Prof. Ernst Pöppel and Dr. Evgeny Gutyrchik, Ludwig Maximilian University of Munich) and the Netherlands (Prof. Laurie Stowe and Prof. Roelien Bastiaanse, University of Groningen) and successfully completed studies in healthy individuals (Dragoy et al., 2012; Yurchenko et al., 2013; Malyutina et al., 2016). We then attempted to apply functional neuroimaging to investigate language processing in patients after stroke and invested effort into starting several projects. However, our expertise at the moment was not sufficient to counter various methodological and conceptual issues inherent to application of functional neuroimaging in the lesioned brain (Specht, 2020), so these projects were discontinued.

Given the historical legacy of Luria's neuropsychology and his lesion approach to understanding the neural substrate of cognitive functions (Luria, 1980), as well as our extensive work with patients with focal lesions following stroke, we were very much interested in pursuing contemporary lesion methods. So, next, having learned the basics of MRI data collection and processing, we started learning modern lesion analysis techniques under the guidance of Prof. Nina F. Dronkers, one of the pioneers of the voxel-based lesion symptom mapping method (Bates et al., 2003). This method allows to evaluate contribution of individual voxels in the brain to the function of interest through statistical modeling. Using this method, our group determined neural regions critical for working memory (Ivanova et al., 2018) and verb naming (Akinina et al., 2019). Currently, we are using the method to explore the neural substrates of different aphasia types, bringing Luria's classification of aphasias into the contemporary neuroscience context (Luria, 1980). Another technique that we have adopted involves diffusion-weighted imaging and tractography analyses (e.g., Ivanova et al., 2016; Zyryanov et al., 2020). These methods allow to investigate the integrity of white-matter fiber pathways in the brain and determine their functional specialization. At this time, more advanced methods such as electrocorticography are also being used, along with further development and elaboration of behavioral and eye tracking studies.

In research development, the key to success has been integration of research with clinical work and incrementality in building a research program. Here, we would really like to emphasize the need to start with short manageable projects. Studies where results can be obtained on a realistic 1–2 years' time scale will serve as a great starting point and foundation for larger projects. Along the same lines, it is advantageous to start with more simple and straightforward methods that are easier to implement compared to more sophisticated neuroimaging techniques. Importantly, it is recommended to explore a method in-depth and complete a single project with it to understand the potential hidden caveats, before using it more widely. In this regard, we clearly made a planning mistake by initially investing a lot of resources into functional neuroimaging studies of language in patients with focal lesions, while the applicability of this method to the stroke population proved to be too tortuous and confounded for our level of expertise then, leading our group to abandon several functional neuroimaging projects without coming to specific results. In hindsight, it would have been more effective to conduct a single functional neuroimaging study and fully complete it, prior to starting other inquiries using the same method.

On the contrary, a prominent example of successful incrementality in research has been our line of lesion studies: it began with the investigation of a specific syndrome (semantic aphasia, Dragoy et al., 2017), followed by larger group studies and more advanced methods (voxel-based lesion symptom mapping, Ivanova et al., 2018; Akinina et al., 2019), with current efforts focused on creating a large lesion database to investigate the neural substrate of different aphasia types. Specifically with regard to lesion symptom mapping, our group has been able to effectively conduct several studies on the same cohort, again something that is highly desirable given the resources involved in carrying out any kind of large group neuroimaging studies with a clinical population. Generally, in the initial stages of development, we would like to warn against getting involved in large-scale projects that are time-consuming, require experience managing a large team and data from multiple sites, and do not yield tractable outcomes in terms of research findings and practical recommendations, as in the beginning it is vital to establish oneself as a group that can achieve stated results.

Further, initial collaborations with internationally renowned experts on joint projects provided the much-needed mentorship and guidance on mastering new skills, while close alliances with clinical sites afforded access to the infrastructure needed for this work (e.g., MRI scanners, EEG systems) and clinical populations. In general, we believe that it is beneficial to have a fluid research agenda in the beginning of establishing a research center. Being open to new avenues of research, new collaborations and new methods will lead to unexpected opportunities, higher productivity and multi-faceted outcomes.

CLINICAL DEVELOPMENTS

Given the interdisciplinary nature of the field of neurolinguistics and the current trends in clinical neurolinguistics in the West, from the beginning we realized that through our research we needed to address practical needs of clinicians working with varied groups of patients with language disorders. In short, we wanted to make a meaningful contribution to improved clinical practice in Russia. We saw two main gaps in clinical work that we felt could be effectively addressed by our group: development of contemporary assessment tools and advancement of novel treatment approaches.

While Russian is one of the ten most commonly spoken languages in the world, there is a clear lack of standardized language assessment tests in Russian (Ivanova and Hallowell, 2013). Historically, a qualitative approach to assessment grounded in Luria's neuropsychological theory has dominated the clinical field in Russia (Luria, 1980; Akhutina, 2016). While this descriptive, qualitative approach is valuable in understanding the mechanisms of cognitive impairments and their neural substrate, it is not readily quantifiable, lacks generalization, and is highly dependent on the expertise of the clinician doing the assessment. As such, lack of standardized measures makes it impossible to provide description of patients in research studies, systematically explore neural mechanisms of language deficits and compare findings cross-linguistically. In terms of clinical work, it makes it challenging to compare patients and protocols across different hospitals and evaluate efficacy of treatments. Thus, when implemented exclusively on its own, the traditional neuropsychological qualitative approach impedes evidence-based practice and research that is contingent on having valid and reliable instruments to quantitatively measure cognitive and language impairments. With a team of linguists, speech-language pathologists, neuropsychologists, and computer scientists, we decided to proactively address this methodological gap.

So, one of the first and most prominent clinical research projects conducted at the International Neurolinguistics Laboratory was the creation, development, standardization and then clinical implementation of a novel comprehensive aphasia test. The aim was to develop a quantitative language battery that was both comprehensive and yet compact to be administered in a clinically feasible time. In 2014, using previously accumulated knowledge on test development (Ivanova and Hallowell, 2013) and clinical expertise, the Russian Aphasia Test (RAT; Ivanova et al., 2021) was designed. The test is meant to provide a multidimensional characterization of impaired and spared aspects of language functioning. The RAT evaluates the critical linguistic levels of processing (phonological, lexical-semantic, syntactic, and discourse) in three different domains: auditory comprehension, repetition, and oral production. During subtest design and stimuli development we took into account various (psycho)linguistic factors known to impact language processing, as well as distinct properties of the Russian language. For instance, consonant distinctive features specific to Russian were manipulated in the nonword discrimination subtest. In the single word comprehension and naming subtests item selection was based on the stimuli database developed earlier by our group (see previous section for more information, Akinina et al., 2014, 2015, http://en.stim-database.ru/) allowing us to account for a number of relevant psycholinguistic parameters (imageability, age of acquisition, name agreement, image agreement, object/action familiarity, visual complexity) in addition to the standard measure of lexical frequency. The sentence comprehension and production subtests took advantage of the flexible word order in Russian to investigate processing of canonical versus noncanonical sentences (see Ivanova et al., 2021 for more details). The test's initial piloting, subsequent extensive normative data collection and standardization involved hundreds of participants and took 5 years (2014–2019). Also, for the final version of the test, our group developed a tabled-based version of the RAT, which further enhanced uniformity of administration, simplified and standardized scoring procedures, facilitating data collection in clinical and research settings. This titanic work has just recently been fully completed (Ivanova et al., 2021).

However, the test's development was not without complications and caveats along the way. This project was overly ambitious at the time it was conceived in 2014, as back then our group had limited experience with test development and organizing such a large-scale project. This led to many predictable blunders along the way: difficulty managing data collected from a large team of students and clinicians; alterations made to the test materials and its structure after standardization has started, requiring repeated data collection; changing technical platforms during the standardization phase, leading to painstakingly manual data aggregation and recoding; and, finally, altering scoring guidelines several times during data analysis requiring complete rescoring of all protocols. In hindsight, we could have implemented this project much more efficiently and with less resources had we started with test adaptation instead of development and focused on select domains and shorter tests, postponing the bigger project for a few years. Today, following tumultuous but eventually successful navigation of logistical and procedural hurdles along the way, the test is now being widely distributed in Russia and is actively used in several large stroke rehabilitation Centers. Additionally, a Tatar language version of the test has been created and is currently in the final stages of standardization (as mentioned previously, it is the second most common language in modern Russia). So, apart from these organizational shortcomings, in the end this project is a poster child of an interdisciplinary project where scientific knowledge, clinical expertise and technological advances were successfully combined to fulfill specific practical needs and enhance clinical practice standards.

From the RAT project, several other important test development initiatives have emerged. Similarly to a lack of standardized aphasia language tests, there was a dearth of standardized quantitative tests for evaluating child language development. This made it impossible to define quantitative norms for language development in Russian and to specify the type and severity of linguistic deficits in children with different developmental disorders in clinical practice and research studies. A test of child language development, the Russian Child Language Assessment Battery (RuCLAB; Lopukhina et al., 2019), was created in 2018 based on the tasks originally implemented in the RAT (Ivanova et al., 2021), with the subtests adapted to assess children's phonological, lexical, morphosyntactic, and discourse skills in comprehension and oral production. The test has been normed in typically developing children and clinical data has been collected in various atypical populations (children with Specific Language Disorder, epilepsy, Autism Spectrum Disorder; e.g., Arutiunian et al., in press). Researchers at the Center have also adapted several other broadly recognized assessment tools into Russian language and have validated them (e.g., Verb and Sentence Test: Akinina and Bastiaanse, 2017; Token Test: Akinina et al., 2019; Aphasia Rapid Test: Buivolova et al., 2020), further contributing to improving clinical practice standards in Russian, advancing evidence-based practice and enabling research studies to be compatible with other international projects.

Another important direction for assessment development has been intraoperative language mapping in tumor patients. Our team developed a linguistically grounded assessment protocol for intraoperative mapping with the aim of preserving language function in patients undergoing surgery for brain tumor or epileptogenic tissue resection (Dragoy et al., 2016b, 2017). Collaboration with surgical centers across the country has helped to broadly distribute this knowledge, stimulate broader use of awake surgeries for language mapping and implement the protocol in clinical practice leading to improved language outcomes following surgery. This highlights how cutting-edge linguistic knowledge can be used to enhance patient outcomes and improve quality of life. Again, this project is another great example of an interdisciplinary approach to resolving a practical problem through collaboration between experts from different fields. Also, it would not be a success without extensive consultations with internationally recognized experts in the field: Dr. Peter Mariën (Free University of Brussels, Belgium), Dr. Henry Colle and Dr. Erik Robert (Algemeen Ziekenhuis Sint-Lucas, Belgium), Dr. Hugues Duffau (Montpellier University Medical Center, France), Dr. Emmanuel Mandonnet (Lariboisière Hospital, Paris, France). Further, the project demonstrates the advantages of starting with a flexible research agenda and being open to new avenues of inquiry, as initially we did not have specific plans or expertise for this line of work, only a general interest in improving language outcomes in varied clinical populations.

The second main direction of our clinical work has been development, adaptation, and promotion of evidence-based speech-language treatment approaches. As in the case of assessments, language therapies used in clinical practice in Russia have remained varied and largely untested. Typically, they are selected based on the clinician's judgement in the absence of quantitative evidence base, so they are again highly dependent on the clinician's expertise. Our group has adapted two contemporary language therapies that were originally developed and proved effective in other languages: Verb Network Strengthening Treatment (VNeST, Edmonds, 2014) and constrained-induced language therapy (CILT, Pulvermüller et al., 2001). We have been conducting a series of studies testing the efficacy of their Russian adaptations (CILT: Ulanov et al., 2019; VNeST: Razmyslovich et al., 2021) in therapy protocols with and without concurrent non-invasive brain stimulation (transcranial direct current stimulation and transcranial magnetic stimulation). We had hoped that these studies would not only provide evidence on the efficacy of these specific treatment protocols adapted into Russian but also introduce a new standard for non-pharmaceutical treatment research in Russia.

So, unlike in the assessment direction of our clinical work, our team started with adaptations of existing therapies rather than with creating new ones, which appeared to be a reasonable choice with regard to feasibility of protocol development. Still, we have encountered several obstacles along the way of treatment studies. First and foremost, as these studies are very labour-intensive and prolonged, it has been difficult to find sufficient human resources within our team for their continuous implementation. This has been a particularly challenging issue because of the chosen experimental designs, which involve intensive language therapy (several hours daily for several weeks), multiple clinicians for group therapy, and a double-blind approach where non-invasive brain stimulation is administered by a clinician different from the one conducting the therapy. Our recommendation for new teams starting treatment studies is to carefully estimate the human resources needed for a particular therapy and experimental design in advance. A wise preliminary step before launching any treatment study would be a precise calculation of how many researchers, and for how long, are needed for participant recruitment, therapy administration, and pre- and post-treatment assessment, particularly if a double-blinded design is used, so that different team members would need to conduct the therapy and the assessment. Choosing a therapy that does not require group administration or intensive regimen and aiming for a small-sample proof-of-concept study rather than a full-scale clinical trial, in our opinion, is a wiser and a more realistic option for a first pass at treatment studies.

Another big challenge in our treatment studies has been to integrate research designs into routine clinical schedule at clinical sites where treatment studies have been conducted. For example, it has been complicated to orchestrate patient selection and pre-treatment baseline testing against a typical rehabilitation center admission timeline that leaves little time for assessment and requires starting the treatment within a very short timeframe. Having encountered this difficulty, we recommend that other new teams prior to starting the study consider whether the routine clinical schedule of the clinical site would allow sufficient time for participant recruitment and extended baseline pre-treatment assessment. If the clinical site is a rehabilitation center accepting returning patients, one solution that we have used is to select, recruit, and pre-test patients at the end of their first rehabilitation course and subsequently admit them into the treatment study during their next admission to the rehabilitation center. Another aspect to consider is whether other routine clinical practices of the clinical site (pharmaceutical treatment, other concurrent treatments such as occupational or physical therapy) could interfere with the language therapy being studied: for example, if these additional therapies/treatments are only prescribed to select patients, this could create unwanted differences between experimental and control groups in the treatment study. Thus, it is important to know in detail the routine practices of the clinical site, so that the research team can request to modify them appropriately and/or to collect relevant information about patients involved in the therapy study.

To date, our own treatment studies are still in progress, and our experience suggests that this avenue of research may not be an optimal choice for new research teams. Greater human resources, more intense involvement and long-term commitment of clinical facilities to the project seem to be the necessary prerequisites for fully-fledged treatment research. Nonetheless, while large-scale treatment studies are beyond the current ability and scope of the Center, we hope that our approach is still a step towards evidence-based clinical practice and can serve as a template that the surrounding speech-language pathology and neuropsychology communities can follow in evaluation of other therapies. Overall, for clinical projects, we would like to stress the importance of collaboration and interdisciplinarity. From the start, one should focus on developing and implementing interdisciplinary projects that combine theories and methodologies from different fields. For successful completion of clinical research projects, it is pivotal to involve researchers from different academic disciplines, specialists with different professional backgrounds along with clinicians and effectively incorporate their knowledge and skill set in design, implementation, analysis, and interpretation of findings, as we have been able to do in our most successful clinical projects to date: development of standardized tests and language mapping protocols for awake brain surgery.

TEACHING AND SUPERVISION

Our teaching activities have been multi-faceted and have gradually increased in scope and breadth over the years. First, individual courses (Experimental Linguistics, Experimental Methods in Psycho- and Neurolinguistics) were offered to students in the bachelor's and master's programs in Linguistics at the HSE University. These courses introduced the students to the basics of experimental design, contemporary psycho- and neurolinguistics theory, and provided an overview of different behavioral and neuroscience techniques. Then, another course (Psychology and Neurophysiology of Speech and Language) was offered to students in the Psychology bachelor's program at the HSE University. This course, on the contrary, assumed previous knowledge of experimental methods but introduced their specific application to the cognitive and neural bases of language processing. These courses were the first courses on psycho- and neurolinguistics at the HSE University and were enthusiastically welcomed by the students.

However, all the above-mentioned standalone courses were of introductory nature and did not include enough hours to teach any hands-on skills necessary for conducting independent research. Eventually, in 2020, the Center for Language and Brain established an educational track in Experimental Linguistics within the bachelor's program in Linguistics at the HSE University. The track expands over the last 2 years of the bachelor's program and includes three courses that provide both in-depth theoretical knowledge and hands-on experience in experimental linguistics. The first course (Psycho- and Neurolinguistics) is taught for two semesters during the first year of the track and provides the theoretical foundation in empirical research methods, neuroanatomy and neurophysiology, and an overview of modern psycho- and neurolinguistics theory. The second year includes two semester-long practically oriented courses (Practicum in Psycholinguistics, Practicum in Neurolinguistics) that address specific research topics and methods more in-depth and offer hands-on experience in experiment programming, data collection, and analysis, et cetera. To the best of our knowledge, this is one of the few undergraduate-level tracks/course series in psycho- and neurolinguistics in the world.

Besides offering individual courses and the educational track, researchers at the Center for Language and Brain have supervised "course research projects" and "summer practical training" of bachelor's and master's students at the HSE University. Both types of activities are mandatory parts of the curriculum in most Russian higher education programs. This is an important strength of the Russian higher education system, providing students with unique hands-on experience already at the undergraduate level. For "course research projects," a student works on an individual research project over the entire academic year and, as a result, writes a research paper and typically defends a presentation. The same is expected for the mandatory bachelor's and master's theses during the last year of study. "Summer practical training" involves work on a hands-on task (for example, collecting or analyzing data) without any literature review, writing or presentation. In most programs, both types of activities are required on an annual basis and students are free to choose a topic and a supervisor. Over the years, staff of the Center for Language and Brain have supervised many "course research projects," theses and "summer practical trainings," typically involving students into their own real ongoing research projects. This has carried inherent risks for the supervisor in case the student fails to complete the assigned part of the project. Nevertheless, this practice has also brought amazing successes, whereby undergraduate students became the driving force of research projects and played an essential role in their successful completion (e.g., Soloukhina and Ivanova, 2018; Zyryanov et al., 2020; Savinova and Malyutina, 2021). Several of the students who completed their "course research projects" or bachelor's theses at the Center later went to study abroad to obtain their master's degree or PhD and then returned to work at the Center as research scientists.

The Center is also building a prolific PhD program, with the first student, who was admitted in 2017, successfully defending her dissertation in 2020. Six other students are currently undertaking their PhD studies under the supervision of the Center staff members, and every year several more are recruited. A recent innovation of the Russian educational system allowed publication-based PhD defenses, and our students eagerly follow this track and defend based on their already published peer-reviewed articles.

Furthermore, the Center represents the HSE University in two recognized international consortia—the European Master's in Clinical Linguistics (EMCL) and the International Doctorate for Experimental Approaches to Language And Brain

(IDEALAB). In both, the Center acts as an associate partner, with a focus on aphasia, structural neuroimaging, and language mapping in awake neurosurgeries. Every year, a few EMCL students visit the Center for a 3-month internship, get integrated into the Center's research environment and write their theses co-supervised by the staff members of the Center. In 2021, our first jointly supervised IDEALAB student defended her dissertation at the University of Groningen (the Netherlands).

Several areas are still not covered by the educational activities of the Center. For example, no educational courses are currently offered to first- and second-year bachelor's students, which would have been helpful for those already starting their "course research projects" under the supervision of the researchers of the Center. Current educational activities are targeting exclusively Linguistics and Psychology students and do not involve any students of medicine-related professions, since there are no such programs at the HSE University. Most importantly, the Center has not yet established any fully independent self-contained educational programs. Still, incrementally, the Center is actively fostering a new generation of scientists, simultaneously advancing both education and research in neurolinguistics. We believe that this teaching-research cycle is absolutely central to scientific progress. Those who are actively involved in research are best enabled to teach the subject matter, bringing cutting-edge advancements to the classroom, and inspire a new generation of scientists through lively lectures, life examples, and tough questions. Young scientists, in turn, bring new energy, ideas, and skills to the research domain. Educational activities require time and effort that is inevitably taken away from research but, in the long run, we believe that this investment is essential for bringing the scientific field forward.

PUBLIC OUTREACH

Since the foundation of the Neurolinguistics Laboratory, we have been actively involved in a variety of public outreach initiatives. First, current educational activity at the Center is not limited to academic courses at the University. The Center holds regular weekly meetings open to the public, entitled Neurolinguistics Thursdays, where researchers of the Center and invited guests speak about current trends in different subfields of neuroscience and discuss their research projects. Also, typically several times a year, the Center hosts workshops where a broader research community can gain practical hands-on knowledge about new research methodologies. A recent example was a workshop on voxel-based lesion symptom mapping that included hands-on sessions addressing all practical steps of using the method, including MRI data preprocessing and manual lesion delineation. These practical workshops also help foster research collaboration and establishment of clinical networks.

One of the key public educational events at the Center is the annual international Summer Neurolinguistics School that has been in session since 2014. The school is positioned both as an educational event for students entering the field and as an academic environment where more advanced researchers can discuss the latest ideas and achievements in the field. Each summer over 100 attendees from different countries come together in Moscow, Russia (or online, since 2020) to gain an in-depth understanding of a given topic presented by renowned guest lecturers. An important feature of the School is that the topic is different every year: in previous years the School has been devoted to aphasia, brain stimulation, neural oscillations, experimental studies across languages, et cetera. It has been a conscious decision to alternate topics so that staff members, students, and the local research community can broaden their horizons and expand their understanding of topics that are not within their area of expertise and that of their close colleagues. Since it aims to target a broad audience, the School has been facing many challenges. For example, since attendees are at very different levels of their education and career, the program needs to be tuned in such way that each lecture is accessible to novices while still offering new knowledge to more advanced attendees. As another example, due to a high number of attendees of different levels, the Schools so far have mostly consisted of lectures and presentations and have included only a minimal number of practical sessions. In spite of these challenges, we believe that the format that covers alternating topics and welcomes students and new researchers is of most value to the community.

The above educational events are aimed at students and professionals from related fields. Apart from them, the Center has been performing public outreach activities targeting the broader public and attempting to present research findings in a format accessible to a wide audience. These have included appearances of staff members in popular science shows, interviews to mass media, involvement with the Russian Dyslexia Association, community projects focused on raising awareness about aphasia, popular science lectures at social centers for the elderly, tours to the Center for middle and high school students, press releases about new publications on the university website. For instance, for raising aphasia awareness, the Center has designed information booklets for caregivers and "ID cards" for individuals with aphasia. They are freely available at the Center's website and paper copies have been disseminated among collaborating speech-language pathologists, so that they can distribute them to patients and caregivers. To the best of our knowledge, these are among the very few Russian-language materials about aphasia available to the public. Another example of public outreach activity of the Center are press releases about new publications. These are plain-language summaries of newly published research findings comprehensible to the broader audience. This format has been established and encouraged by the university, so press releases are placed at the university website, in both English and Russian, and offered for repost to mass media.

Unlike educational events for students and related professionals, public outreach activities of the Center have not been regular, due to the shortage of time and human resources. Nonetheless, we hope that even sporadic events or materials targeting the wider community may start word-of-mouth dissemination of current evidence-based views and research findings. Besides, the Center itself has also benefited from public outreach activities. Any outreach to a broad audience has helped

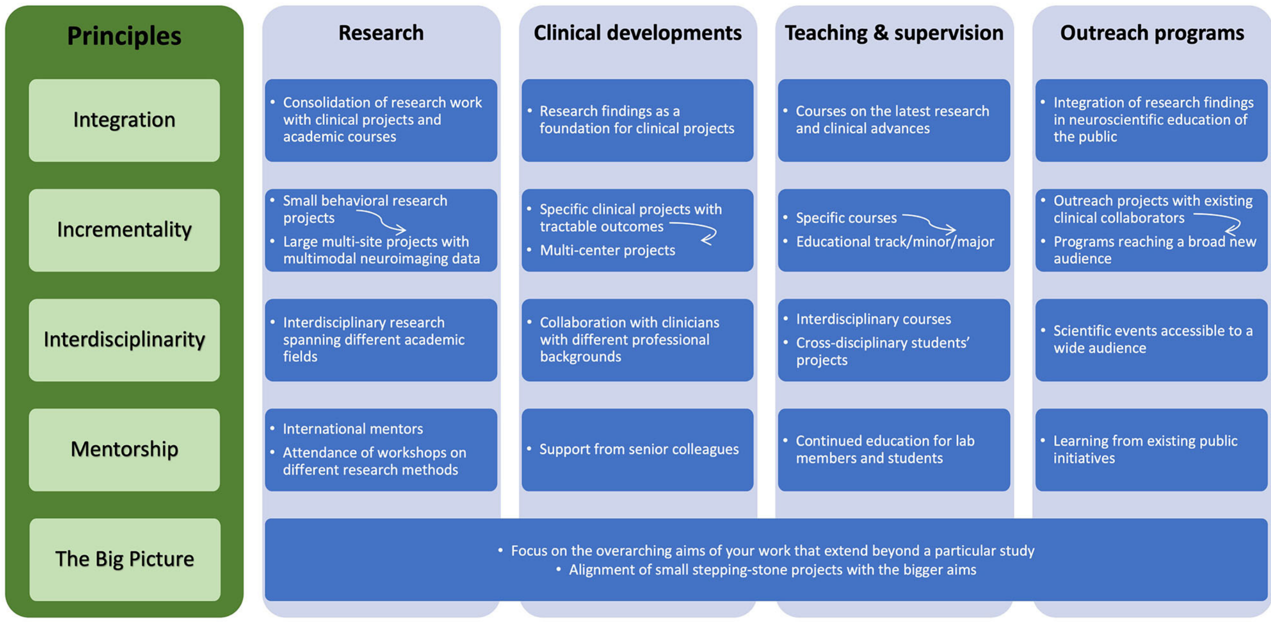

FIGURE 2 | Summary of the main working principles of scientific and educational program development as they apply to different areas of activity and service (research, clinical work, teaching and supervision, and public outreach).

with volunteer recruitment for the Center's studies. Outreach to clinicians helps to establish new collaborations and/or to learn more about current practices and needs of practicing clinicians. Outreach to high school students may inspire some of them to enroll at the university and get involved in the Center's research activities. Overall, while systematic public outreach activities currently remain beyond the Center's capacities, we have found that embracing occasional opportunities for public outreach brings mutual benefits and incrementally increases public scientific knowledge.

THE SCIENTIFIC SCENE IN 2021

We have outlined above the four pillars—research, clinical work, teaching, and public outreach work—that have contributed to the advancement of neurolinguistics in Russia. This path started on pure enthusiasm with specific research projects and evolved into the largest interdisciplinary neurolinguistics research center in Russia. We would like to conclude the account of our scientific journey by summarizing working principles that we believe contributed to the success of what seemed like a very audacious endeavor a decade ago: *integration, incrementality, interdisciplinarity, mentorship,* and keeping *the Big Picture* in focus. **Figure 2** provides an overview of these main working principles as they apply to different areas of activity and service (research, clinical developments, teaching and supervision, public outreach programs).

First of all, *integration* of all our lines of work has been central to our success. Intermixing and interweaving research, clinical, and academic work has been pivotal for scientific advancements and formulation of evidence-based practices. Rigorous experimental research offers a sound foundation for clinical projects and helps build an evidence base for assessment and treatment approaches. In turn, clinical interactions afford unique insights into the psychological and neural mechanisms of cognition and impart crucial motivation for research. Both research and clinical work provide irreplaceable experiences that translate into captivating teaching material. At the same time, academic work and involving students in all stages of the research process fuel research activity and enhance productivity. Together, research, clinical work, and teaching interact to support, promote and inspire each other. From the beginning one should consider carefully developing in parallel, instead of focusing on just one aspect such as research, and largely integrating these interrelated scientific activities.

In terms of *incrementality*, starting with small doable research projects seems to be the most efficient way of building comprehensive research and academic programs. Large endeavors are built on small stepping stones. This principle of incrementality also holds for funding acquisition, where starting with smaller grants and slowly building up to applying for larger grants is a more productive and feasible strategy.

While incrementally building your research program and initially being flexible in your research agenda, you should not lose track of the overarching aims of your work that extend beyond a particular study by keeping *the Big Picture* in focus. What are the big questions/issues/knowledge gaps that your group is trying to address? What change in current research, clinical, and academic practices do you hope to bring about? Aligning small stepping-stone projects with those bigger aims (such as, for example, promoting standardization and evidence-based practices in assessment of language disorders) will ensure that progress is made in the right direction leading to long-lasting impact on the field and current practices in neuroscientific disciplines.

Interdisciplinarity is an important aspect of contemporary research. Today, innovation and scientific advancements happen at intersection of different disciplines. Thus, from the beginning it is advantageous to include researchers and professionals with different backgrounds in your team and find collaborators from other disciplines, enabling you to successfully implement interdisciplinary projects.

Per *mentorship*, it is pivotal to find international mentors to support your journey as you begin to establish your independent programs. Again, this is particularly crucial in the first stages, as you will need advice and support on grant writing, building a professional network, and finding connections through which you can learn about new methodologies. At the same time, support and promote your students as they are the future scientists. Invest time into training them, offer interesting and motivating research experiences, endorse independent inquiries, and encourage their continuous education.

There are also several practical aspects to developing new research, clinical, and educational programs. On the funding side, it is important to ensure stability, so that staff can stay on the projects while continuing to develop professionally. Building a network of collaborating clinical sites is another vector of development that is of pivotal importance. Having access to clinical resources and different patient populations are largely key to prolific neuroscientific research. Here, from the beginning, devoting effort and time to translational and clinically motivated research is crucial, as it offers mutually beneficial interactions to clinical sites and thus promotes closer collaborations. Additionally, it is worthwhile to invest time in developing resources and procedures that will support numerous projects in the future: stimuli libraries, participant databases with behavioral and neuroimaging data, robust pipelines, digitization of data collection, script documentation for automatic data processing. While originally implementing some of these practices might be time consuming and seem almost inefficient in terms of addressing the current agenda, these efforts will pay off in the long run, ensuring standardization and efficiency in your working practices.

We believe that following these outlined principles can substantially aid in establishing new neuroscientific research centers in countries where neuroscience and experimental research have been underrepresented and thus promote implementation of evidence-based approaches in healthcare, and improvement of neuroscientific education and knowledge in a wider community. Finally, in the end this type of pioneering work is about passion. Ignite and follow your passion, for when you are passionate about something, you will find ways to succeed.

AUTHOR CONTRIBUTIONS

MI, SM, and OD jointly contributed to the conception of the paper and were involved at different stages in funding acquisition for the Neurolinguistics Laboratory and now the Center for Language and Brain at the HSE University. MI wrote the original draft of the manuscript, that was expanded by SM and OD. All authors contributed to manuscript revision, read, and approved the submitted version.

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Teaching the Science in Neuroscience to Protect From Neuromyths: From Courses to Fieldwork

Alejandra Carboni[1,2†], *Alejandro Maiche*[1,2†] and *Juan C. Valle-Lisboa*[2,3*†]

[1] Centro de Investigación Básica en Psicología e Instituto de Fundamentos y Métodos, Facultad de Psicología, Universidad de la República, Montevideo, Uruguay, [2] Centro Interdisciplinario de Cognición Para la Enseñanza y el Aprendizaje, Universidad de la República, Montevideo, Uruguay, [3] Sección Biofísica y Biología de Sistemas, Facultad de Ciencias, Universidad de la República, Montevideo, Uruguay

In recent decades, Cognitive Neuroscience has evolved from a rather arcane field trying to understand how the brain supports mental activities, to one that contributes to public policies. In this article, we focus on the contributions from Cognitive Neuroscience to Education. This line of research has produced a great deal of information that can potentially help in the transformation of Education, promoting interventions that help in several domains including literacy and math learning, social skills and science. The growth of the Neurosciences has also created a public demand for knowledge and a market for neuro-products to fulfill these demands, through books, booklets, courses, apps and websites. These products are not always based on scientific findings and coupled to the complexities of the scientific theories and evidence, have led to the propagation of misconceptions and the perpetuation of neuromyths. This is particularly harmful for educators because these misconceptions might make them abandon useful practices in favor of others not sustained by evidence. In order to bridge the gap between Education and Neuroscience, we have been conducting, since 2013, a set of activities that put educators and scientists to work together in research projects. The participation goes from discussing the research results of our projects to being part and deciding aspects of the field interventions. Another strategy consists of a course centered around the applications of Neuroscience to Education and their empirical and theoretical bases. These two strategies have to be compared to popularization efforts that just present Neuroscientific results. We show that the more the educators are involved in the discussion of the methodological bases of Neuroscientific knowledge, be it in the course or as part of a stay, the better they manage the underlying concepts. We argue that this is due to the understanding of scientific principles, which leads to a more profound comprehension of what the evidence can and cannot support, thus shielding teachers from the false allure of some commercial neuro-products. We discuss the three approaches and present our efforts to determine whether they lead to a strong understanding of the conceptual and empirical base of Neuroscience.

Keywords: neuroscience of education, learning, cognitive neuroscience, fieldwork, neuromyths, teacher training

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Rutgers, The State University of New Jersey, United States

Correspondence:
Juan C. Valle-Lisboa
juancvl@fcien.edu.uy

† These authors have contributed equally to this work

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INTRODUCTION

The rapid development of neurosciences in the last few decades motivated the search for applications of this body of knowledge and an increase of the interest of the public (Herculano-Houzel, 2002; Altimus et al., 2020). As any advanced field, Neuroscience is complex, thus the potential for excessive simplifications, tergiversation or even outright falsification is high. The appearance of Neuroscience in the public discourse led to the emergence of several neuromyths that spread through the population. The natural interest of the educators in Neuroscience sparked the development of a market of several products aimed at educators and parents that were supposedly based on Neuroscience, but the support is scarce. Early on, in 1997, John Bruer (1997) published his now classical paper "Education and the brain: A bridge too far" pointing to several holes in the Neuro-educational literature and products, and promoting a skeptical (but hopeful) view on the then available application of Neuroscience to Education. Also, Bruer suggested that there was indeed an available bridge in Cognitive and Educational Psychology having the required body of knowledge to impact on Education. Despite making an instant classic, the paper did not stop the neuromarketing of dubious ideas that helped promote several wrong or simplified ideas, usually called neuromyths.

The concept of neuromyth refers to a series of misconceptions or baseless beliefs that arise from the wrong interpretation of neuroscience research results and its application in education or other contexts (OECD, 2002). Several factors related to the emergence and proliferation of neuromyths have been identified: differences in training and technical language between the educational and neuroscientific fields (Howard-Jones, 2014), limited access to peer-reviewed scientific journals (Ansari and Coch, 2006), overgeneralization from neuroscience studies with individual neurons to educational policy (Goswami, 2006), and preference for explanations that seem based on scientific evidence even though there is no evidence in this regard (McCabe and Castel, 2008; Weisberg et al., 2008).

One aspect of the lists of neuromyths used in several papers (Herculano-Houzel, 2002; Dekker et al., 2012; Gleichgerrcht et al., 2015) is that they are variable in their character. For instance, the difficulty of the questions in the Neuromyth scale (Howard-Jones et al., 2009; Dekker et al., 2012) is variable, as should be if the scale is to measure anything. More important to us here, the questions are of very different types. Consider for instance, these 4 questions: (1) *We mostly only use 10% of our brains*, (2) *Drinking < 6–8 glasses of water a day can cause the brain to shrink*, (3) *Keeping a phone number in memory until dialling, recalling recent events and distant experiences, all use the same memory system*, (4) *Memory is stored in the brain much like as in a computer. That is, each memory goes into a tiny piece of the brain*. Neuromyth (1) is so imprecise that it could be argued that it is not even false, it is unscientific. Neuromyth (2) is easily spotted as false with usual experience; Neuromyth (3) contradicts a detailed and important piece of knowledge that required the careful study of patients and experimental studies during several years to be established (Squire, 2009). Lastly, neuromyth (4) can be said to be defended by some well known cognitive scientists (Gallistel and King, 2009) and even has some empirical support (Johansson et al., 2014).

Thus in a sense the list of neuromyths can change at any time, and maybe some of the less improbable assertions can be re-interpreted under a new framework. The problem is not so much having wrong beliefs about the brain; after all in a growing science there has to be some level of controversies that are part of "normal science" (Kuhn, 1962). The problem is that while professional scientists can gauge the evidence base of any claim and search for the relevant evidence to rule out some assertion, non-professionals are at the mercy of the best communicators, not necessarily the most truthful.

We believe that the only way out of this problem is to develop strategies to teach scientific thinking, that is to teach the public, and specifically the Educators, how scientists deal with the different opinions around a set of propositions about a body of knowledge. Here we describe our attempts to develop a strategy and a preliminary evaluation of the success of the different alternatives. First we describe the origin of our proposal. After describing the basis for our strategies we present the evaluations that show that teacher directed courses about the theoretical bases of Cognitive Neuroscience and the participation within research groups are viable strategies to give a rigorous science education. We create a questionnaire to assess the teacher's knowledge of epistemological principles, and show that the pattern of responses suggests that although teachers that take part in research groups are not better at answering the neuromyth questionnaire than those that took our teacher directed course, some of them show signs of thinking similarly to researchers. Despite the limitations of the evaluation, we believe that participation in research can help teachers develop a scientific mindset which allows them to better navigate the specialized literature and the commercial offerings.

In the last few years we have been leading a set of projects aimed at the development of the Science of Learning and its applications to Education. We were part of the organizing and steering committee of the Latin American School for Education, Cognitive and Neural Sciences, a summer school that had 7 editions: three times in Chile, two times in Argentina, one in Brazil and one in Uruguay (for the Uruguayan edition see, http://2014.laschool4education.org). These Summer Schools brought together consolidated researchers on the Science of Learning (Meltzoff et al., 2009; Ansari, 2021) together with graduate students or junior PIs in order to further the development of application of this nascent field to Education. It was born as the result of a meeting that took place in Santiago de Chile in 2007, which brought together scientists interested in the Brain/Education barrier and led to the Santiago Declaration (https://www.jsmf.org/santiagodeclaration/), in part a re-evaluation of Bruer's paper main thrust.

Judging not only by the opinion of the alumni and Faculty involved, but also from the standpoint of the collaborative projects and publications that the Schools promoted, these instances have been a great success launching a series of studies in our region (Goldin et al., 2014; Sigman et al., 2014; Strauss et al., 2014; Dillon et al., 2015; Odic et al., 2016; Valle-Lisboa et al., 2016). Likewise, it has created a scientific community with high dedication to the popularization of this new Science[1] especially to educators[2].

Motivated by the environment and international collaborations that were forged in LASchools, each group of researchers have been taking different perspectives for the implementation in their countries of that interface between education and cognitive science. Thus, in Uruguay, together with a group of colleagues from Neuroscience, Psychology and Computer Science, we created in 2015 the Interdisciplinary Center for Cognition for Teaching and Learning (https://www.cicea.ei.udelar.edu.uy/) and in 2016 the first master in cognitive science in Uruguay (https://www.mcc.ei.udelar.edu.uy/) with a marked profile towards topics related to the Learning Sciences.

In this framework, in 2017 we launched the first symposium of education, cognition and neuroscience that brings together some consolidated researchers from the LASchool's environment together with researchers, educators and policy decision makers. Besides the researchers and students that attend the symposium, more than 400 educators attend to the symposium motivated by their interest in the possibilities that this new[3] interface between education and cognitive science could offer. The result was a 4-day event where international speakers (such as Manuel Carreiras, Justin Halberda, Sidarta Ribeiro, Mariano Sigman, Linda Smith) presented their latest results and participated in round tables together with local policy makers analyzing questions such as "What contributions can Cognitive Science make to Education in Uruguay " or "What is the kind of University of Education that Uruguay needs? " All these instances of the Symposium are available on the YouTube channel[4] of CICEA.

In parallel to these singular activities[5], in Uruguay we have been organizing annually (since 2018) a course directed to teachers and educators (https://www.cicea.ei.udelar.edu.uy/curso-aportes-de-las-ciencias-cognitivas-a-la-educacion-2/) with the main idea to show the fundamental principles of cognitive neuroscience, with the specific objective of discussing the impacts the new Science of Learning has on the theories they use to guide their practice. With this idea in mind, the course goes over general principles of cognition, learning, teaching, plasticity, motivation and also some specific topics of this interface like math cognition and language. This course brings annually more than 200 educators so it could be considered part of the permanent link that educators in Uruguay have with the research and advances of cognitive sciences and learning sciences.

Lastly we started a new, but more costly effort, namely, organizing scientific stays for teachers to do research applied to education in our labs. In this way, a limited number of educators have become progressively approaching the different research groups that work in Uruguay on these topics. These educators have been integrated in research groups by providing their experience and their links with the Educational System at the same time that they participate in some of the research projects that these groups develop. This experience has been novel and challenging since it has allowed us to see the difficulties of interdisciplinary work in practice. However, most researchers evaluate it as a positive experience although it is still premature to draw conclusions about results.

We conceive our efforts in three levels or strategies. In the first place, our popularization efforts, or scientific symposia where teachers are invited to participate. The second strategy is the yearly course on Cognitive Science and Education. The third strategy is the organization of research stays for teachers. The first strategy is defined by exposure to Neuroscience that might be relevant for Education, but only through popularization instances (magazine or newspaper articles, popularization talks, booklets, etc.) or by short symposia, that despite gathering important researchers, are too short to allow the transmission of a great deal of knowledge. The second strategy is clearly defined by the participation in any of the editions of our course of "Contributions of cognitive sciences to education." This course includes lectures and paper discussion sessions, where participants are directed to analyze the methodology of the results presented. The third strategy implies taking part in research activities within any of the research groups of CICEA, for at least 1 month.

In this article we present our preliminary analysis of the impact these three strategies have in the teacher's knowledge of Cognitive Science and its applicability to Education. In order to approach this evaluation we ran two surveys. One survey is an adapted extract from the usual Neuromyth measuring scales (Howard-Jones, 2014). The other is a set of six questions related to general epistemological and methodological questions. As we will show, despite the fact that much more work needs to be done, these epistemological/methodological questions complement the neuromyth scale, adding a dimension related to procedural knowledge. We conclude by proposing that the core of understanding of Neuroscience in a non-specialist public, depends on a broader Scientific Education.

METHODS

Participants

Previously to applying the survey, we defined four categories with which we categorized participants in four different groups. Group 1 (we named them, the Interested, group): included teachers from any education level interested in Cognitive Neuroscience but that at most might have attended popularization talks related to the topic ($N = 48$); Group 2 (Attended): is composed of teachers that participated in any of the editions of the course "Contributions of cognitive sciences to education" (Aportes de la ciencias cognitivas a la educación) ($N = 60$); Group 3 (Collaborated): included teachers that are taking part in any of our Educational projects as members of the research team ($N = 11$) and Group 4 (Researchers): composed of post graduate students and junior

[1]https://www.youtube.com/watch?v=O4xiApaSprM.
[2]https://www.fundaciontelefonica.uy/noticias/aula-en-linea-un-aporte-a-la-formacion-semipresencial-de-los-docentes/.
[3]This viewpoint was not known for most of educators in Uruguay at that time.
[4]https://www.youtube.com/playlist?list=PL_MnlbUI01SOU0193gpBrMJWAH692UujK.
[5]The 2nd symposium of education, cognition and neuroscience is scheduled for November of this year (2021) and we hope to have more than 500 Uruguay educators, but also from other countries of the region. See more details here: http://www.succc.org.uy/es/events/conference_2020.

Investigators, which will serve as a gold standard ($N = 18$). The sample comprised 140 participants linked to education and cognitive neuroscience aged between 20 and 69 years old (mean age = 42.9, SD = 10.7), and was selected using the following criteria: first we contacted all the teachers (12) that were taking part in research activities. Only one did not answer the survey. In order to have a comparable "gold standard" we recruited all young researchers and graduate students from our lab. We also contacted all attendees to the two "Aportes" courses (192) who completed the evaluations during the course and recorded all the responses we received before we started to analyze the data ($N = 60$). We aimed for a similar number of teachers who did not attend any of our courses or seminars, nor took part in any other activity we organized. The survey was promoted through teachers' mail-lists, and through social networks. All interested participants were directed to an online survey (google form) and answered the questions anonymously. Participants completed a questionnaire allowing us to determine whether they fulfilled the inclusion criteria. Three subjects were excluded because their performance was more than 2.5 standard deviations from the mean score (see below, data analysis).

Procedure

Participants were asked to answer through a Likert scale (1–5) the degree of agreement with 38 statements related to neuroscience and education. 32 assertions were selected and adapted from Howard-Jones et al. (2009) survey. Adaptation of the items involved straightforward improvements in the expression to support clarification in Spanish. Additionally, 6 more statements were included in order to evaluate general aspects related to epistemological investigation knowledge (please see **Supplementary Material** for all the questions used).

Data Analysis

As we mentioned before, we sent surveys to four groups of people. We eliminated the data from subjects whose score differed from the global (i.e., considering all subjects irrespective of group) mean score by more than 2.5 global standard deviations; this resulted in the elimination of the data from three participants that had scores lower than the mean; according to the classification in groups, these participants were part of group 1.

Missing Data Imputation

We replaced missing values with the median of the responses for each item. Overall, we imputed <1.1% of the data.

In all analyses we used the scikit.learn python library for clustering analyses, pandas data frames and scipy.stats tools (statistical tests).

RESULTS

Following standard procedures, we eliminated the items whose correlations with the full score were negative. These negative correlations imply that some participants who get high scores, are getting low scores on those items, and some participants having overall low scores, answered those questions correctly. The removal of these items ensures that we only keep items that measure the same abilities as the rest.

The eliminated items were:

a. 'El consumo regular de refrescos con cafeína reduce el estado de alerta', [Regular drinking of caffeinated soft drinks reduces alertness].
b. 'Los alumnos muestran preferencias individuales sobre el modo en que reciben información (por ejemplo, visual, auditiva, cinestésica) '[Individual learners show preferences for the mode in which they receive information (e.g., visual, auditory, kinaesthetic)].

As we inverted scores of the questions whose correct answer was 1 in the Likert scale, the maximum achievable score in the Neuromyth Scale after these manipulations was 150, the result of obtaining 5 points in each of the 30 remaining items. The Cronbach's Alpha obtained was $\chi = 0.68$ which is acceptable for our purposes.

In **Table 1** we show the scores for each group after all these manipulations.

In **Figure 1** we present the distribution of scores in the Neuromyths scale. By inspection it can be seen that the group of researchers is clearly separated from the other groups. It also seems that the second group has a higher median score than the first group. The third group is small and variable.

This intuition is confirmed by the analysis. A Kruskal-Wallis test shows that there is a statistically significant difference between the score distribution of the groups ($H = 30.062$, df = 3, $p = 1.34\text{e}{-06}$). The *post hoc* comparison using Dunn's test with false discovery rate correction shows that the scores of group 4 are different from all the other groups, that group 2 and group 3 are different from group 1 and that group 2 and 3 do not differ in their mean scores (**Table 2**).

The Pattern of Responses

In order to deepen our understanding of the knowledge of each group, we turn to analyze the pattern of the responses. At the outset, we expected that the members of the fourth group would have a small variability in their responses. Surprisingly this is not the case. But this variability can be attributed to different patterns of response in each of the groups. In this sense, despite having the same overall scores, groups might differ in their pattern of responses. To analyze the patter of responses we first run a PCA with all the answers to the Neuromyth questionnaires. The first four principal components (PCs) only explain 39 % of the variance. To analyze the response pattern we clustered the four groups using k-means to fit three clusters to all the questionnaire responses. Despite the fact that PCA captures little variance, in order to visualized the clusters obtained with k-means, we project all the responses to the plane formed by the first two principal components. We show the results of the k-means clustering in the PCA plane in **Figure 2**, where we use a different marker for each group and a color for each cluster.

Even though PCA is not capturing enough variance, notice that aside from some exceptions the first PC separates the three groups quite well. This first PC correlates strongly

TABLE 1 | Group composition and descriptive parameters of the neuromyth survey results.

Group	No. of members	Median score	Inter quartile interval	Q1	Q3
Interested	48	109.5	10.5	105.5	116.0
Attended	60	115.5	11.0	111.0	122.0
Collaborated	11	116.0	8.5	111.5	120.0
Researchers	18	130.5	9.0	124.0	133.0

Q1 and Q3 are the first and third quartile, respectively.

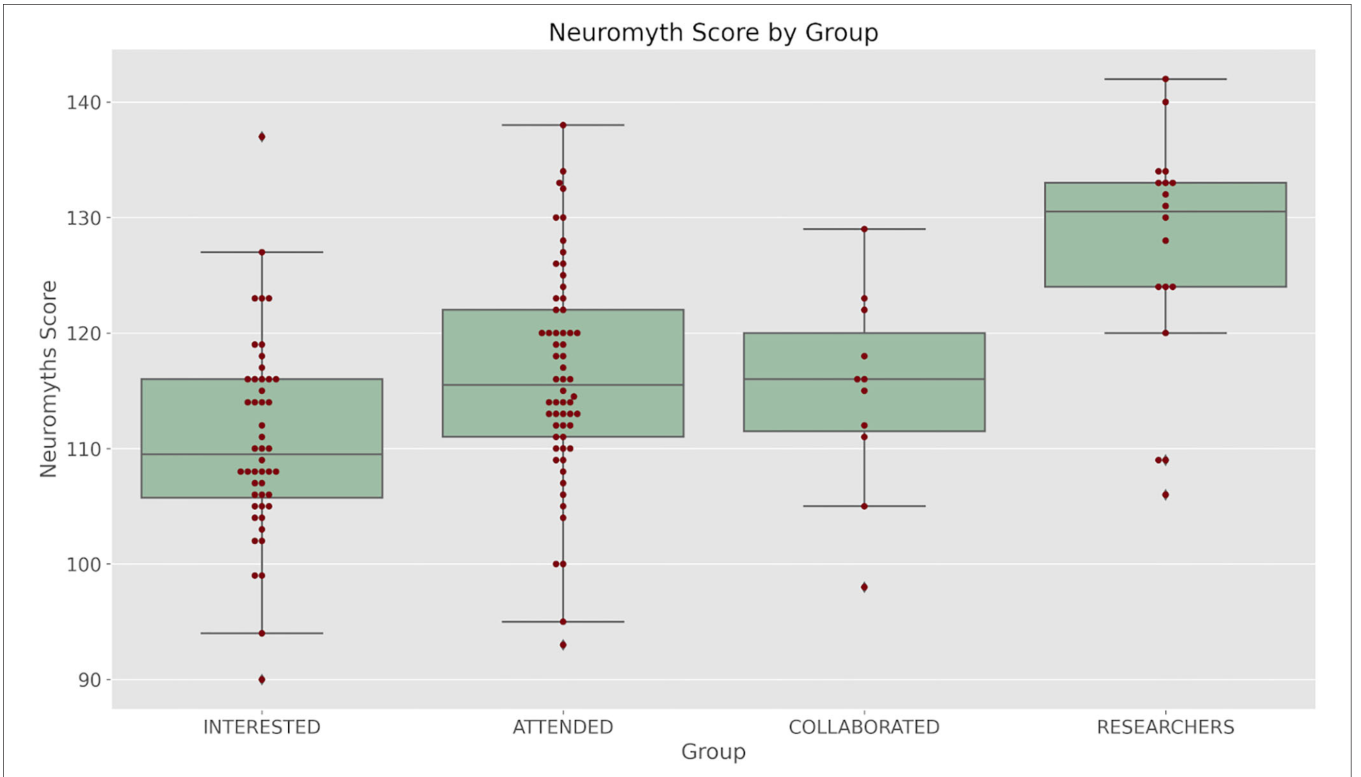

FIGURE 1 | Boxplots showing the distributions of Neuromyth scale scores: INTERESTED refers to a group of teachers not related to our courses and stays. ATTENDED refers to a group of teachers that have participated in the regular course relating Cognitive Science and Education. COLLABORATED refers to those teachers that besides taking part in our course have done or are doing a research stay at our lab. RESEARCHERS Refers to Master students, PhD students or researchers from our lab. See the text for further details.

with correct responses to the following questions (see **Supplementary Material**):

- *Short bouts of coordination exercises can improve integration of left and right hemispheric brain function.*
- *Environments that are rich in stimulus improve the brains of pre-school children.*
- *It is with the brain, and not the heart, that we experience happiness, anger, and fear.*

The second PC correlates with the correct response to:

- *Learning problems associated with developmental differences in brain function cannot be remediated by education,*

and with the incorrect response to:

- *Learning is not due to the addition of new cells to the brain.*
- *The mind is the result of the action of the spirit, or of the soul, on the brain.*

As a result, a high PC1 score and medium PC2 score is associated with most of the members of group 4 which are mostly in cluster three. Most of the individuals from group 1 are in the first cluster, whereas both group 2 and 3 are distributed between clusters 1, 2, and 3. In **Table 3** we show the detailed clustering attribution.

Thus the same results as the comparison between total scores are apparent with the clustering method, i.e., group 4 and group 1 are extremely different, but both group 2 and 3 share part with group 1 and 4. In that sense, the pattern of responses is similar between groups 2 and 3.

Methodological and Epistemological Questionnaire

As a part of an ongoing strategy to analyze the epistemological and methodological knowledge of our students and collaborators, we applied a modified questionnaire adapted from our School of Psychology methodological undergraduate courses. The details of the questionnaire are shown in the Methodology section. In **Figure 3** we show the scores obtained by each group in this questionnaire. A Kruskal-Wallis test shows that the scores differ ($H = 12.82$, $p = 0.005$).

TABLE 2 | Dunn's test with False Discovery Rate (FDR) correction.

	Interested	Attended	Collaborated	Researchers
Interested	–	**0.00107**	0.0519	**1.80E−07**
Attended		–	0.267	**0.001073**
Collaborated			–	**0.006124**
Researchers				–

The table shows the adjusted exact p-values (bold marks the significant differences at 0.01 level for ease of visualization) of each pairwise comparison between mean neuromyth scale scores of each group.

A *post-hoc* Dunn test shows that only the scores from GROUP 4 and GROUP 1 ($p = 0.0029$) and GROUP 4 and GROUP 2 ($p = 0.0026$) differ. All other p are higher than 0.05.

We further use the pattern of responses to these six questions as clustering features following the procedures we applied to the other questionnaire. In **Figure 4** we show the results of the clustering algorithm.

We used PCA to visualize the cluster obtained. Here the first two PCs capture 55 % of the variance.

The first PC correlates to the incorrect answer to these questions:

- *A primary school applies a method for teaching math, then takes an exam and all of its students pass. We cannot claim that the method is effective for teaching mathematics*
- *A Nobel prize winning researcher claims that the technique he developed many years ago makes it possible to assess whether a person is infected by a virus. This does not show that the technique can be used to assess whether a person is infected with a virus.*
- *A group of students summarize texts and perform well on tests. This proves that summarizing is a good way to study.*

The second PC correlates to the incorrect answers to these two questions:

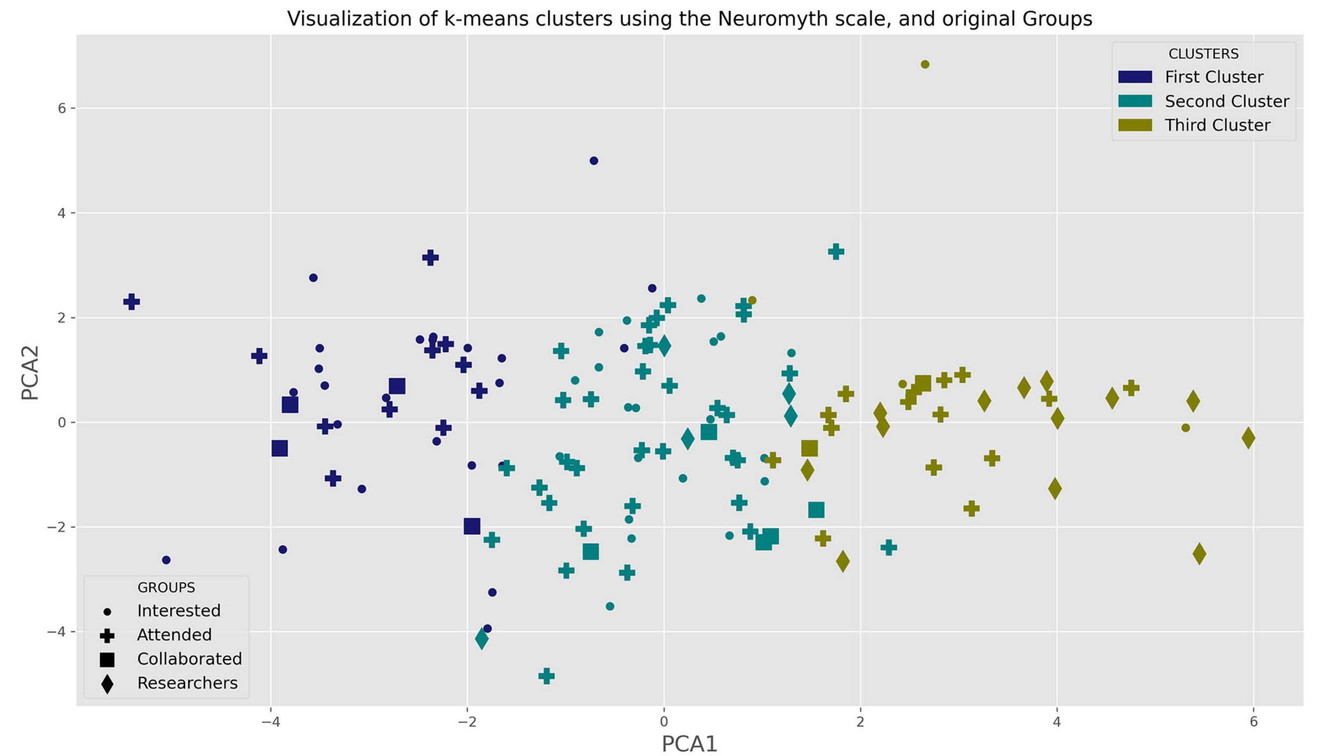

FIGURE 2 | 2D projection and clustering of the responses to the Neuromyth questionnaire. The responses to the Neuromyth Questionnaire were projected to the 2 dimensional space spanned by the principal components of responses. The full set of responses was used to cluster the respondents in three clusters using k-means algorithm. In the graph, the Groups are coded by the markers and the clusters obtained by k-means are coded using colors. Notice that some points seem to be misplaced, but this is due to the fact that the PCA does not capture enough variance (see **Supplementary Material** for details of the PCA results).

TABLE 3 | Results of clustering participants by their answers in the neuromyth scale.

	Cluster 1	Cluster 2	Cluster 3	Total
Interested	24 (50%)	20 (42%)	4 (8%)	48
Attended	11 (18 %)	34 (57 %)	15 (25 %)	60
Collaborated	4 (36 %)	5 (46 %)	2 (18 %)	11
Researchers	0	5 (28 %)	13 (72 %)	18
Total	39	64	34	137

The clustering was obtained using the k-means algorithm, with 3 clusters. The distribution among clusters is different in the different groups ($\chi^2 = 40.02$, $p = 4.52e{-}07$). Post-hoc comparisons with FDR correction show that the cluster distribution of group Interested differs from that of group Attended ($p = 0.0022$), and from Researchers ($p = 1.49\times10^{-6}$) but not from Collaborated ($p>0.5$). Attended also differs from Researchers ($p < 0.003$) but not from Collaborated ($p > 0.4$). Collaborated and Researchers also have different distributions among clusters ($p = 0.0061$).

- *In order to evaluate an initial literacy program, children are randomly selected from various classes in the country, dividing them into two statistically indistinguishable groups. One of the groups learn through the new program and the other through a regular program. If external evaluators find statistically significant advantages in those children who participated in the new program, it is possible to claim that it is more effective for initial literacy than the usual program.*
- *A researcher analyzes the relationship between a set of variables and reading scores. He finds that those children who have higher relative weight read better than those who have low weight. Therefore, the researcher shows that increasing weight improves reading.*

and to the correct answer to the questionnaire

- *A group of students summarize texts and perform well on tests. This proves that summarizing is a good way to study.*

See **Supplementary Materials** for details of the PCA.

In **Table 4** we detail the participation of each group in each cluster. In the legend of this table, we analyze the statistical properties of the distribution.

DISCUSSION

Neuroscience is one of the fastest growing sciences in the last decades, both in terms of papers published and of the impact it has on the public. This impact is not only due to the scientific advances in understanding the brain, but especially because it can give new insights into old and persistent problems. One of the areas where it is hoped that Neuroscience can greatly improve human life is in the field of Education. Indeed, several approaches towards basing Educational practices in Cognitive Neuroscience have been emerging in different places of the world. The initial reasonable skepticism (Bruer, 1997) has been replaced by optimistic approaches applying Cognitive Neuroscience to Education in reading (Hruby et al., 2011; Potier Watkins et al., 2019), mathematics (Halberda et al., 2008; Dillon et al., 2017; Judd and Klingberg, 2021), social skills learning (Gerdes et al., 2011), science education (Zimmerman and Klahr, 2018), motivation (Di Domenico and Ryan, 2017) attention (Stevens and Bavelier, 2012), conceptual development (Mareschal, 2016) and creativity (Onarheim and Friis-Olivarius, 2013) among others [but see Bowers (2016) for criticism of the neurobiological aspects of these approaches]. A few years ago, as we started participating in the regional effort to develop Cognitive Neuroscience and its applications to Education we sought to produce applications to Education. Together with the use of digital technology this allowed us to study and intervene in an educational setting (Valle-Lisboa et al., 2016).

Coupled to this renewed interest in Neuroscience, a commercial promotion of supposedly Neuroscience-based programs and products has been growing and promising several simplistic solutions to Educational problems and rebranding old strategies under a "neuro" slogan with the purpose of increasing the revenues. A group of false beliefs on the workings of the brain, called neuromyths, are widely spread and threaten to replace genuine deep knowledge in the population as a whole and, potentially more dangerously, within the teacher professionals.

From the beginning of our applied research projects we realized the importance of Education to counter these neuromyths and their impact on educators. Nevertheless, it has been shown that those teachers that are more informed about neuroscience tend to be more vulnerable to neuromyths (Dekker et al., 2012) probably because they are more exposed to low quality materials. It follows that any program geared at educating teachers about neuroscience has to be carefully designed in order to avoid unintendedly promoting neuromyths.

In this article we have shown that among all teachers and educators that are interested in Neuroscience, those that take part in our longer duration activities, be them courses or the participation in research stays, are less vulnerable to neuromyths than those that only attend our popularization talks or read popularization publications. Although the results presented come from a correlational study that was a spinoff of our efforts to establish a definite teaching strategy, we believe that this is not just due to differences in motivation. Indeed as a part of the initial questionnaire we asked participants about their interests and all participants declared their intention to apply Neuroscience to education. Moreover members of group 1 also attended other short talks or symposia, so we believe that there are no systematic differences in motivation between the three groups of teachers. Although we are starting an experimental study in order to clearly separate causal and non-causal effects, if the causal link is confirmed, it would suggest that the difference observed in our results might be caused by the participation in the long-lasting activities. This would not really be surprising. Most popularization activities only transmit a superficial explanation of the phenomena involved, and thus at the same time that they promote the interest in the topic, when they are not presenting the empirical basis of the claims, these activities do not promote a deep understanding of neuroscience. Our course involves over 30 h of lectures and paper discussions, connecting teachers to the fundamentals of the discipline. It is not surprising that participants in our course are better at responding to the questions, although the specific content of most of these questions is not taught directly in the classes.

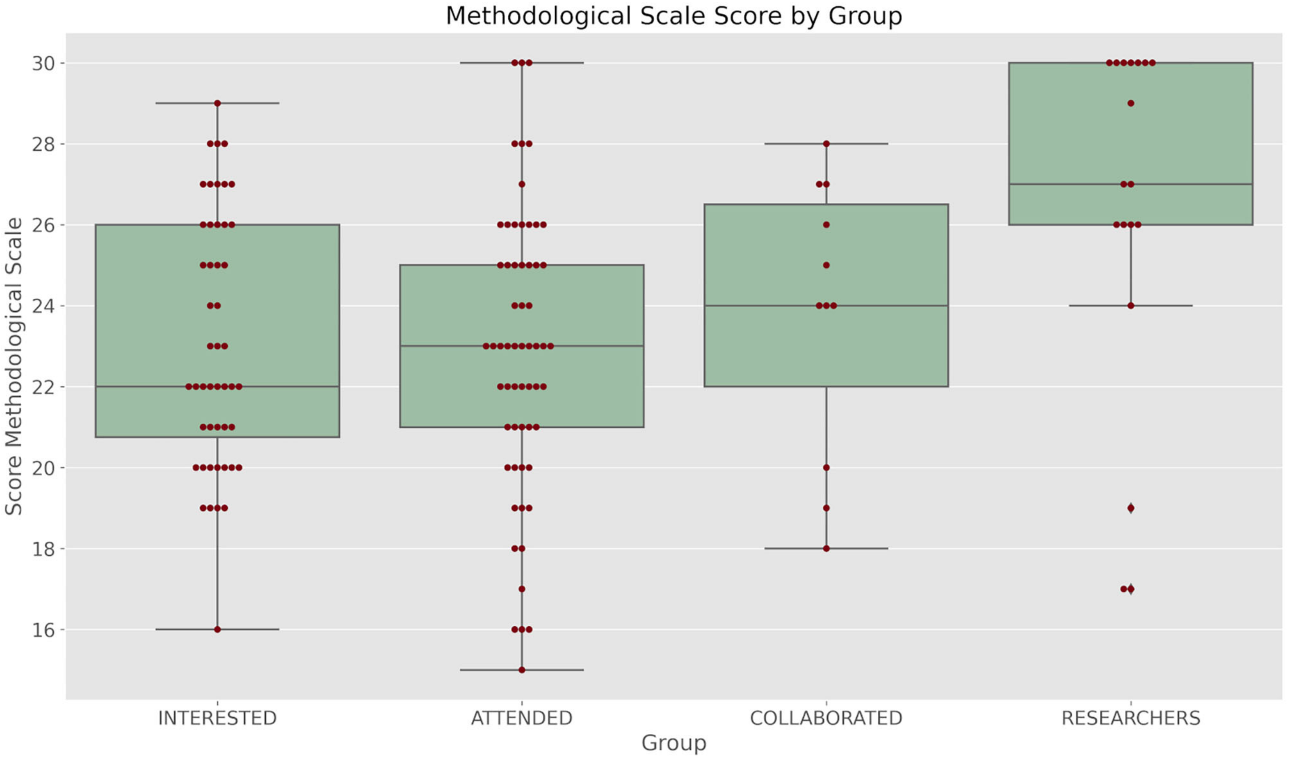

FIGURE 3 | Boxplots of the scores obtained in the methodological/epistemological questionnaire by each group.

Interestingly, most of the teachers that decided to participate in our research teams also had a higher score in the Neuromyth scale than the general group of teachers. Although every instance of participation of teachers in research groups involved reading scientific articles, we did not make sure that all the educators read the same articles. Nevertheless, their responses did not differ from those of the group of teachers that participated in our courses. This means that both groups get a comparable amount of Neuroscientific information. Of course the scientific stays are not easily scalable unless they are included as part of the regular teacher training (Ansari, 2021). Thus, the question remains about whether there are differential benefits of the two long-term strategies. We approached this question with the creation of an *ad hoc* questionnaire probing the epistemological and methodological knowledge of participants, adapting a set of questions we use in undergraduate courses. The responses show a great variability within groups, so only the group of graduate students shows a consistent difference with respect to the other groups. Nevertheless, the pattern of responses shows that some of the teachers that participated in the scientific stays tend to have a similar pattern of responses to the scientists and graduate students. In particular, notice that for the Neuromyth scale, the pattern of responses clearly separates in three groups, mainly driven by the response to the questions related to lateralization, the presence of excess stimulation in classrooms, the role of the brain in emotions and the lack of plasticity. More importantly, when a methodological questionnaire was applied, the questions related to experimental design were the most discriminating ones. These are in general hard questions in a sense that they are the core of scientific research and take some time to be deeply comprehended.

These are preliminary results, in particular because we used a convenience sample and the power might not be enough to detect other differences. If these results are confirmed in a controlled experiment, they would show that hands-on research activities can be an effective way to transmit the limits and implications of scientific research, allowing teachers to gauge the evidence and decide for themselves. In a way, this is the same that happens in Medicine, where medical doctors are supposed to read and interpret the findings of a wide range of disciplines to get a clearer picture of diagnoses and treatments. The same could happen in Education, where teachers should be prepared to critically assess the evidence coming from different sources, including Neuroscience. In a sense this is much more important than knowing specific bits of Neuroscientific knowledge. It is not impossible that some parts of our knowledge about Neuroscience change (for instance our ideas about learning and plasticity, Gallistel and King, 2009; Johansson et al., 2014). In fact, most epistemological considerations point to the possibility of change of scientific models and ideas. In that sense, the list of statements one should know would change and would require a constant updating. We subscribe the proposal, instead,

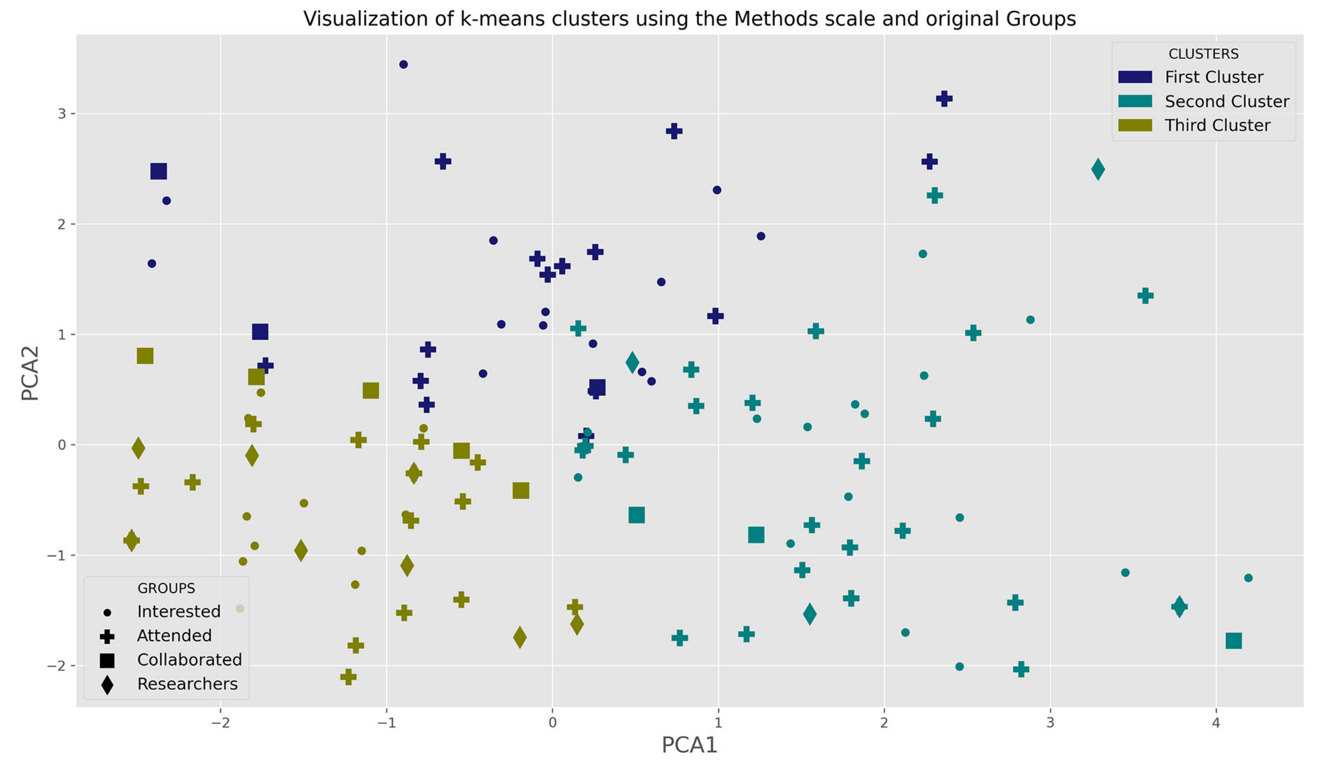

FIGURE 4 | Results of k-means clustering algorithm, projected over the plane spanned by the two first PCA dimensions. The markers represent the groups, whereas the color represents the clusters. In the plane, the lower left corner is associated with the third cluster, the lower right with the second cluster and the upper center with the first cluster. Most members of the RESEARCHERS group (diamond) are in the third cluster, and just a few are in the second cluster with none in the first cluster. Both INTERESTED (points) and ATTENDED (crosses) are more evenly distributed, whereas COLLABORATED (squares), tends to be closer to the RESEARCHERS distribution (it is indistinguishable statistically, see **Table 4**); there are 5 squares in that cluster. Although due to low numbers it is also indistinguishable from the first two groups, notice that whereas in the clustering based on the Neuromyth scale, COLLABORATED and RESEARCHERS were statistically different (**Table 3**), here they are not.

TABLE 4 | Clusters obtained from the pattern of responses to the methodological questionnaire.

Group	Cluster 1	Cluster 2	Cluster 3	Total
Interested	15 (31 %)	17 (36 %)	16 (33 %)	48
Attended	15 (25 %)	25 (42 %)	20 (33 %)	60
Collaborated	3 (27 %)	3 (27 %)	5 (45 %)	11
Researchers	0	4 (22 %)	14 (78 %)	18
Total	33	49	55	137

The different groups are differentially distributed among clusters. (χ^2 = 14.83, $p < 0.05$). Post hoc comparison with FDR correction shows that the group Interested and group Researchers are different ($p < 0.01$) as well as Attended and Researchers ($p < 0.01$). None of the other groups show statistically significant differences in their distributions among clusters (all ps > 0.05).

that we should focus on educating the public in general, and teachers in particular, to be able to understand the design and methodology of studies involved in gathering relevant evidence for their fields (Pasquinelli, 2012; Ansari, 2021). This will surely require important amounts of declarative knowledge, but it should also include epistemological and methodological knowledge, which are probably better obtained by engaging in direct scientific activities. In order to confirm the relevance of this line of action we are starting a carefully controlled intervention that can test whether this is in fact the case or not.

DATA AVAILABILITY STATEMENT

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

ETHICS STATEMENT

The studies involving human participants were reviewed and approved by Comité de Ética de la Investigación, Facultad de Psicología, Universidad de la República. The participants provided their consent to participate in this study, by accepting to enter the online form, after receving information about the study.

AUTHOR CONTRIBUTIONS

AC, AM, and JV-L conceived the study and designed the data collection steps. Most of the analysis has been done by JV-L. The results were thoroughly discussed by all authors. All authors participated equally in the writing of the manuscript.

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SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fnhum.2021.718399/full#supplementary-material

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On Neuroeducation: Why and How to Improve Neuroscientific Literacy in Educational Professionals

Jelle Jolles[1]* *and Dietsje D. Jolles*[2]

[1] *Faculty of Behavioural and Movement Sciences, Vrije Universiteit Amsterdam, Amsterdam, Netherlands,* [2] *Leiden Institute for Brain and Cognition, Institute of Education and Child Studies, Faculty of Social and Behavioural Sciences, Leiden University, Leiden, Netherlands*

New findings from the neurosciences receive much interest for use in the applied field of education. For the past 15 years, neuroeducation and the application of neuroscience knowledge were seen to have promise, but there is presently some lack of progress. The present paper states that this is due to several factors. Neuromyths are still prevalent, and there is a confusion of tongues between the many neurodisciplines and the domains of behavioral and educational sciences. Second, a focus upon cognitive neuroimaging research has yielded findings that are scientifically relevant, but cannot be used for direct application in the classroom. A third factor pertains to the emphasis which has been on didactics and teaching, whereas the promise of neuroeducation for the teacher may lie more on pedagogical inspiration and support. This article states that the most important knowledge and insights have to do with the notion of *brain plasticity*; the vision that development is driven by an interaction between a person's biology and the social system. This helps individuals to select and process information, and to adapt to the personal environment. The paper describes how brain maturation and neuropsychological development extend through the important period of adolescence and emergent adulthood. Over this long period, there is a major development of the Executive Functions (EFs) that are essential for both cognitive learning, social behavior and emotional processing and, eventually, personal growth. The paper describes the basic neuroscience knowledge and insights – or "neuroscientific literacy" – that the educational professional should have to understand and appreciate the above-described themes. The authors formulate a proposal for four themes of neuroscience content "that every teacher should know." These four themes are based on the Neuroscience Core Concepts formulated by the Society for Neuroscience. The authors emphasize that integrating neuroscientific knowledge and insights in the field of education should not be a one-way street; attempts directed at improving neuroscientific literacy are a transdisciplinary undertaking. Teacher trainers, experts from the neuroscience fields but also behavioral scientists from applied fields (notable applied neuropsychologists) should all contribute to for the educational innovations needed.

Keywords: neuroeducation, brain development, executive functions, neuroscientific literacy, education, adolescence, brain plasticity, neuromyth

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***Correspondence:**
Jelle Jolles
j.jolles@vu.nl

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INTRODUCTION

In the past two decades there has been a rapid rise in the interest in research findings about the brain, especially in relation to learning, human cognition, and behavior. Advancing research methods have improved our understanding of the mechanisms underlying the way we learn, think, reason, and feel, from the perspective of the functioning of the human brain. Furthermore, researchers are improving our insights into the maturation of the brain and its relation to developmental changes in cognition, emotional functioning, and behavior (e.g., Mayer, 2017). The relevance of these findings for the domain of education is expressed in new books (e.g., Tokuhama-Espinosa, 2014; Blakemore, 2018; Steinberg, 2019; Dehaene, 2020), in much visited meetings such as the Learning and the Brain conferences in the United States, and the increasing interest in the topic of Neuroeducation, and in the establishment of new journals such as "Mind, Brain and Education" and "Trends in Neuroscience and Education." These and other journals are important in encouraging the crosstalk between the multidimensional domains of neuroscience, behavioral and cognitive science, and the field of education (Ansari et al., 2017; Thomas et al., 2019).

Since the Decade of the Brain in the 1990ies (Jones and Mendell, 1999) and especially the OECD report on "the birth of a learning science" (OECD, 2007), there is also a rise in the interest of educators and policy makers for issues related to brain and education. Yet there is still some hesitation and even resistance to the notion that insights from neuroscience could ever be applied in the classroom, and some education researchers remain suspicious of what they regard as "a hype" surrounding educational neuroscience (e.g., Bowers, 2016; see Thomas et al., 2020 for an elaboration). Hence, the translation of neuroscience knowledge to the field of education and its successful application in educational settings is not at all settled. A major stumbling block in this translation is that educators who are really interested in applicable knowledge from the neurosciences have trouble finding the right books, articles and trustable internet sites. Moreover, university courses or programs integrating insights from the fields of neuroscience and education are still rare and not within reach of the majority of educators. The difficulty of finding reliable, accessible and relevant knowledge may be one of the reasons that many educational professionals believe in the so-called "neuromyths" (OECD, 2007; Dekker et al., 2012; Howard-Jones, 2014; Macdonald et al., 2017).

In terms of the metaphor used by Bruer (1997) and others (e.g., Ansari et al., 2017; Goswami, 2019): there are not enough bridges over the river that separates the field of education from the domain of the neurosciences, and the bridges that exists are not easily accessible to educators. Even among scientists in the field of Mind, Brain, and Education, there is no consensus as to which knowledge and insights about brain structure and function could be relevant for use in the domain of education, and which knowledge and insights is not. Therefore, it is the purpose of the present article to contribute in this respect. We defend the position that knowledge about the brain does not always have a *direct* relevance for applied fields, yet everybody should be familiar with the basic facts about brain structure and function, as well as its development, analogous to the common knowledge we have about the heart, about digestive function and the respiratory system.

With respect to the term "neuroscientific literacy" we use in this paper, we employ a definition which is based upon the earlier definitions proposed by Herculano-Houzel (2002) and others (e.g., Horvath et al., 2018; Im et al., 2018). Howard-Jones and coworkers (e.g., Howard-Jones, 2010; Deligiannidi and Howard-Jones, 2015) defined neuroscience literacy – or "neuroliteracy" – in terms of "understanding about the brain and how it functions." Neuroscience literacy as we see it, can be defined as "*the knowledge and understanding of brain systems and processes required for cognitive and affective functioning across the lifespan, including neuroscience issues related to disease, disorders, and dysfunction, as well as notions how humans interact with their environment and with each other because of their nervous system characteristics*." Note that it has been suggested to extend the notion of neuroscientific literacy, in order to incorporate "*the adoption of a critical-reflective teaching method*" (e.g., Bergmann et al., 2017). We appreciate the relevance of such an extension, but will use the former definition for the present article because of the earlier literature which used a similar definition. We propose that it is essential to improve neuroscientific literacy in terms of the educator's understanding of the knowledge base that exists about brain structure and function. In addition, educators should be given the tools to decide what scientific evidence is valid and how to judge its quality. This is essential to allow them to reflect on the potential applicability. Experts in the field state that such insights can support teachers' professional judgment and give them a better understanding of their students (Ansari et al., 2017; Goswami, 2019; see also Sigman et al., 2014). This will impact their pedagogical knowledge and give additional weight to their educational approach.

The present paper intends to be a perspective article which presents a viewpoint on "the new science of learning" (OECD, 2007) which is not only based upon insights from cognitive science, behavioral science and educational science but also on knowledge obtained in the neurosciences including neuropsychology. Importantly, this paper is *not* meant to provide neuroscientific support for specific kinds of educational practices, or to give concrete advice that is directly applicable in the classroom. Rather, it aims to provide an overview of relevant neuroscience concepts and an explanation for why this type of research is important for educational practice. We argue that basic principles of neuroscience and neuropsychology should be part of the knowledge base of teachers and integrated into teacher training. Teachers will benefit from knowledge and insights into the learning student because it may give them a new perspective to reflect on their pedagogical approach and professional experience and, thereby, their teaching.

ON NEUROEDUCATION

On the Science of Mind, Brain and Education and Related Fields

The focus in the present paper lies on the multidimensional domain of education and the possible relevance of insights from the science of *Mind, Brain and Education* (MBE, see Tokuhama-Espinosa, 2011). MBE is closely related to the new science of learning (OECD, 2007) and is also known as *Educational Neuroscience*. It is an interdisciplinary research field that seeks to integrate knowledge about the neural mechanisms of learning and development with insights from the field of education, and aims to improve our understanding of the way environmental factors influence brain structure and function, and thereby impact the conditions under which learning takes place. Accordingly, MBE is also a fundamental science that studies how education changes the brain (Ansari et al., 2017) and how interventions aimed at improving brain function can impact learning. It is therefore a misunderstanding that MBE research *primarily* aspires to improve educational practice and policy. Even so, the translation to education, which we refer to as *Neuroeducation* in the current article, is an important objective in the field of MBE. Generally, MBE, and neuroeducation in particular, aim to support the dialog between researchers and practitioners in the fields of neuroscience and education, and to encourage transdisciplinary partnerships (Sigman et al., 2014). Such partnerships have the potential to improve educational outcomes by integrating teachers' practical experience with scientific insights into the mechanisms of attention, motivation, executive functions, and memory, and the effects of sleep, health, stress, and other conditions that influence learning.

It is important to note that the domain of neuroscience is vast, and extends far beyond the research approach in which brain structure and function are measured via brain imaging techniques such as Magnetic Resonance Imaging (MRI). Accordingly, it is better to speak of "the neurosciences"; the field encompasses at least 40 disciplines and subdisciplines, ranging from neurobiology, neuroanatomy, and neurophysiology to neurology, neuropsychology, and even neurophilosophy. Neuroscientists work together with many disciplines such as psychologists, health care professionals, philosophers, and educational professionals.

The science of MBE is closely related to and overlaps with *Cognitive Neuroscience*: the science that represents the convergence of cognitive psychology and neuroscience (Gazzaniga et al., 2008). Cognitive neuroscientists study the brain mechanisms underlying complex human behaviors such as language, learning, decision making and emotional processing. Likewise, MBE has links to the domains of *Affective Neuroscience* and *Social Neuroscience* (e.g., Immordino-Yang, 2011; see also Mills et al., 2014; Chen et al., 2018), which are connected to the field of Cognitive Neuroscience, but have their focus upon emotional processing and social behavior rather than cognition *per se*.

Another related field is *Developmental Cognitive Neuroscience,* which concentrates on the developing individual. Developmental cognitive neuroscientists study cognitive development and learning in relation to changes in brain structure and function (see Ansari et al., 2017; Thomas et al., 2019). For example, they evaluate how neural activation and task performance are influenced by developmental changes in cognitive functions such as attention (Posner and Rothbart, 2013), working memory, and executive functioning (Diamond, 2013). In addition, they investigate the influence of external, non-psychological factors such as sleep (Sharman et al., 2020) and exercise (Hillman et al., 2008; Mandolesi et al., 2018). Beside the study of cognitive functions, developmental cognitive neuroscientists also study the interaction with the social environment and the influence of emotional factors and motivation (e.g., Somerville and Casey, 2010; Mills et al., 2014; Blakemore, 2018). In fact, in the past few years there has been a tremendous increase in our understanding of "the social brain of the adolescent" (Crone and Dahl, 2012; Knoll et al., 2015), and its relation to natural curiosity, exploratory behavior and learning (Dahl et al., 2018; Steinberg, 2019).

Finally, the field of MBE is also related to the discipline of *Neuropsychology*. Neuropsychology is a behavioral science in its focus upon human behavior, cognition and emotion but also a neuroscience in that it strives to understand the individual by application of insights from neuroscience (Lezak et al., 2012; Kolb and Whishaw, 2015). Many applied neuropsychologists work with patients suffering from cognitive or behavioral problems in relation to brain dysfunction, developmental disorders, or cognitive aging.

The present paper places its focus upon Developmental Cognitive Neuroscience and Neuropsychology, but also on the basic neurosciences that are needed to understand the development and maturation of the brain and its impact on learning and educational achievement.

The Challenge of Interacting Levels of Analysis

A major challenge that the field of MBE faces is that brain and behavior are studied on different levels of analysis (Willingham, 2009; Van Leijenhorst et al., 2017). At the lowest levels of analysis, neuronal processes and brain anatomy are examined in great detail, for example by recording of activity in individual neurons or by studying brain tissues and cells under a microscope. At higher levels of analysis, neuroscientists study brain structures or even entire brain networks, sometimes in relation to cognitive abilities. These cognitive abilities are generally studied in isolation, using well-controlled but relatively artificial tasks. Even higher levels of analysis focus on the child, the class, or the entire school system. Educational scientists find themselves on these higher levels of analyses, studying the child in interaction with its environment. On the higher levels of analysis, learning is often examined in naturalistic settings that unfold over the course of weeks or even months, rather than minutes or seconds, as is the general case in research on lower levels of analysis.

Because of the differences in granularity, complexity, and timescale, it is often difficult to draw inferences from one level of analysis to another (Willingham, 2009). Therefore, when translating findings from cognitive neuroscience to the field of education, it is important to realize that the "whole child" is more than the "sum of its parts." Akin to a dish that gets a unique flavor due to the interaction between different ingredients, children cannot and should not be reduced to a collection of separate cognitive functions, affective tendencies, and personality traits, let alone a collection of neural predispositions. Moreover, just like the appreciation of food is influenced by the method of preparation, children are influenced by their immediate environment, including the family, their class, the teacher and school, as well as the broader society and culture that they grow up in. Contextual theories such as Bronfenbrenner's bioecological systems theory argue that children participate in and are influenced by multiple interacting social contexts (Bronfenbrenner, 2005). Importantly, contextual influences can go all the way back to the level of the brain, and even to the level of genes (Gottlieb, 2007). Psychobiological research has revealed that there are bidirectional interactions between all levels of analysis, including genes, brain, behavior, and the social and cultural environment, suggesting that processes at lower levels of analysis should not be seen as causal factors driving functioning at higher levels of analysis, but as components of a larger dynamic system (Gottlieb, 2007; Greenberg, 2007). Therefore, when studying developmental changes, for example during the transition from childhood into adolescence, attention should be paid to all those multiple interacting levels of change, including physical, cognitive, and emotional changes, as well as changes in the social context and responsibilities (Dahl et al., 2018).

Educators have the difficult job of integrating all these different aspects of children's functioning and behavior. Yet, in our opinion, this does not mean that knowledge of separate cognitive processes and neural mechanisms is not relevant to education. We argue that conceptual knowledge about the developing mind and brain could help teachers to look more systematically at their students, lessons, or classroom interactions. This would allow them to make more informed decisions about how to approach a particular situation. For example, research in the domain of cognitive neuroscience suggests that children benefit from an "enriched" learning environment, including activities that trigger curiosity and stimulate their language and thinking abilities, but neuroscientific findings also illustrate the importance of focused attention and preventing distraction (Dehaene, 2020). It is the teacher's task to weigh these different insights, along with findings from other domains, and find the right approach for each child in each particular situation.

Neuroeducation: Problems and Pitfalls

Through the years there have been criticisms on the notion that neuroscience knowledge could impact educational decisions and approaches. In his seminal paper, Bruer (1997) states that the translation of neuroscience to the field of education is "a bridge too far." Likewise, in the past two decades, other authors have been skeptical about the relevance of neuroscientific findings for education, concluding that "only evidence from psychological experiments that examine behavior is relevant to education" (e.g., Bowers, 2016) and that "social problems require social solutions, not reduction to neural mechanisms" (e.g., Lalancette and Campbell, 2012; see Ansari et al., 2017 for discussion). Recently, Willingham (2018), discussed in Thomas et al. (2019) noted that knowledge of psychological theory or neuroscience findings is not necessary to teachers. According to Willingham, teachers should "understand children" and be able to observe the child in order to find patterns and consistencies in their cognition, motivation and emotion. On good grounds, however, others have argued that such a perspective is unnecessarily narrow (e.g., Howard-Jones, 2014; Horvath and Donoghue, 2016; Ansari et al., 2017; Thomas et al., 2019), given the multidimensional character of the educational domain. Nonetheless, it is important to emphasize that neuroeducation cannot and should not be *prescriptive*, in the sense that neuroscientific insights will be able to tell teachers what to do in a particular situation. Instead, neuroeducation should aim for *conceptual translation*, providing a broader context to understand the way children learn and develop. This could lead to better theories about education, and aid teachers in their decision making (e.g., Horvath and Donoghue, 2016). Or, as Schwartz et al. (2012) put it: "In education, there are few things as practical as a good theory," referring to Kurt Lewin's famous Maxim.

Besides arguments related to the relevance of neuroscience to education, there are also concerns about the reliability of the methodology and its practicality for describing the functioning of an individual subject (Thomas et al., 2019). As Thomas and colleagues describe, some of these criticisms are exaggerated by focusing solely on functional brain imaging, thereby negating the fact that the neurosciences involve a multitude of different domains, overlapping with behavioral and cognitive sciences. Recent papers from eminent researchers provide examples of neuroscientific evidence that are not derived from neuroimaging research but have major implications for education (see Fuhrmann et al., 2015; Diamond and Ling, 2016; Galvan, 2017; Goswami, 2019). Nevertheless, there are indeed limitations to neuroscientific methodology (which is also the case for other types of research), and it is of utmost importance that researchers remain cautious when interpreting and communicating their findings. Yet, awareness of methodological limitations should encourage rather than impede interdisciplinary collaboration. Only by integrating insights from different domains can we move the field forward.

Neuroeducation: On Neuromyths, and the Seductive Allure of Neuroscience

A major problem in the application of neuroscience insights into education has to do with the so-called "neuromyths." "Neuromyths are misconceptions about brain function generated by a misunderstanding, a misreading, or a misquoting of facts scientifically established (by brain research) to make a case for use of brain research in education and other contexts" (OECD, 2007; Dekker et al., 2012; Macdonald et al., 2017). As an example, the most persistent neuromyth (see Dekker et al., 2012) states that individuals should be taught according to their preferred learning style – whether they are a visual, auditory or kinesthetic learner. However, many research papers have been published in the past decade, showing again and again that learning styles do not exist (see Macdonald et al., 2017). A belief in this myth could be harmful to the learning individual as the "preferred learning style" does not always provide the best fit for the learning goal and hampers the development of experience with other learning strategies. This also applies to another often-mentioned myth concerning the idea that everyone is either a left- or right-brained learner (e.g., Dekker et al., 2012). So, the danger of neuromyths is that they are (inappropriately) applied to the classroom, leading to less effective teaching and learning. In addition to that, the discussion and uncertainty surrounding neuromyths could lead to a lack of confidence in the field of neuroscience and the many neuroscience facts which deepen our understanding of the learning process (this article, see also Dehaene, 2020). Therefore, educational professionals should become aware of the possibility that their convictions about neuroscience can have a negative impact upon their teaching. This implies that teachers should adopt a critical-reflective teaching method as suggested by Bergmann et al. (2017) and others.

Besides neuromyths, we also need to be mindful of the convincing power that neuroscientific findings may have on public opinion. Neuroscientists and educational professionals alike have warned us for the "seductive allure of neuroscience explanations" (e.g., McCabe and Castel, 2008; Weisberg et al., 2008) that may sway people's opinion about political, legal, or educational issues or trap them into buying something that they do not need. Although others have shown that the seductive allure of neuroscience is not as ubiquitous as initially suggested (Farah and Hook, 2013), there are circumstances under which individuals are particularly prone to biased judgment when presented with neuroscientific evidence. For example, Scurich and Shniderman (2014) showed that people find neuroscientific evidence more persuasive when these findings are in line with their prior beliefs, suggesting that neuroscientific evidence may fall prey to the same thinking biases that are evident in the appraisal of other types of (scientific) evidence. Future research should further investigate the circumstances and individual characteristics that moderate the seductive allure of neuroscience, as this allure effect may contribute to the spread of neuromyths and biased judgment.

On the positive side, the fact that a belief in neuromyths is prevalent among teachers can be taken as an indication that they stand favorable to the notion that knowledge about the brain is relevant for learning and teaching. Interestingly, we have obtained strong indications that the prevalence of "believe in neuromyths" is highest in educational professionals who have the best knowledge about the brain (Dekker et al., 2012). We take this as an indication that it is difficult for teachers to find valid neuroscientific knowledge on the internet and in their professional literature. This underscores the notion that a valid and reliable knowledge base about neuroscience – neuroscience literacy – is urgently needed because having an understanding of neuroscience will enable educators not to use or promote misconceptions about the brain, and avoid the acceptance of educational products that cannot stand the critic.

Example: The Appeal of "Brain-Training" Programs

It is probable that neuromyths and the seductive allure of neuroscience may have played a role in the popularity of so-called "brain-training" programs. These are computerized training programs targeting fundamental cognitive abilities, such as working memory and the executive functions (Diamond and Ling, 2016) which are described in section "Development and Training of the Executive Functions." The idea of brain-training gained traction after initially promising findings of training-induced changes in cognitive task performance (see Jolles and Crone, 2012; Constantinidis and Klingberg, 2016), and even measures of fluid intelligence (Jaeggi et al., 2008). The impression that playing brain-training games could make you smarter and "unlock your brain's full potential" was appealing to the general public. Hence, well before the scientific community had gathered enough evidence for its effectiveness, commercial parties started selling brain-training software. The claims that are made by these companies are often over-exaggerated and not backed-up by solid research (Simons et al., 2016). Moreover, the term "brain-training," which is mostly used by commercial parties rather than by researchers themselves, is misleading as it suggests that neural changes are specific to this particular type of training. This completely pushes aside the fact that learning *always* changes the brain (Jolles and Crone, 2012). Besides, findings of training-induced modulation of brain function are largely irrelevant to the question of whether brain-training has any practical value beyond the lab. This point was also made by Simons and colleagues who published a comprehensive 82-page review article on the effectiveness of brain-training interventions. Their conclusion: brain-training frequently improves performance on the trained tasks and often on closely related tasks, but there is currently little evidence that it improves real-world outcomes (Simons et al., 2016). Yet, by the time this paper was published, the brain-training industry had become a multi-million-dollar business. It goes without saying that consumers are free to play brain-training games if they choose to do so, but the question is whether they would pass their time in a different way if they were sufficiently informed about the current scientific basis of these programs. This example illustrates the importance of careful communication of research findings to educators and the general public and investing in a greater (neuro)scientific literacy.

Neuroeducation: Chances and Possibilities

Notwithstanding the critics mentioned above, there is a strong and positive attitude toward a new "science of learning" in which insights from the neurosciences, cognitive science, educational science and the behavioral sciences are merged (Sigman et al., 2014; Mayer, 2017; Thomas et al., 2019; Dehaene, 2020). Thus, scientific activities in the "Decade of the Brain" in the 1990s (Jones and Mendell, 1999) have led to major advances in the crosstalk between basic neurosciences such as neurobiology, neurophysiology, neurochemistry, neuroanatomy and others, and the exchange with applied disciplines such as neurology, psychiatry and clinical neuropsychology. This has yielded breakthroughs in our understanding of brain structure and brain function in normal conditions (e.g., in cognitive development and cognitive aging) and in pathology (e.g., many neurological diseases and psychiatric conditions). In addition, since then there has been a tremendous technological advance in the *in vivo* imaging of brain function, notably by functional MRI, and EEG techniques. This enabled researchers to investigate the human brain in action and has led to the theoretical advances that made the science of MBE viable as a field (e.g., Goswami, 2003; Ansari, 2005; Tokuhama-Espinosa, 2011). Brain imaging experiments informed us about mechanisms underlying the processes of reading, arithmetic and other academic achievements (see Dehaene, 2020) and provided clues as to the neuroscientific basis of conditions such as dyslexia, dyscalculia, ADHD, depressed mood and anxiety-related problems. Yet, up till today, the findings from cognitive neuroscience are considered to be important for progress on the scientific domain but not yet sufficient to be of direct help in the design of innovative teaching techniques and didactics and in educational interventions (Ansari et al., 2017). The promise of neuroscience research for the field of education may lie more in the use of insights related to the interaction between learning and development and in the internal and contextual factors that impact learning, including the application of pedagogical principles (Thomas et al., 2019; see also Tokuhama-Espinosa, 2014). Many of these ideas are grounded in a broader evolutionary framework which suggests that learning and development are evolved features allowing the individual to adapt to their current and future environment (Bjorklund, 2018, 2020). The key insights are outlined in section "BRAIN DEVELOPMENT, LEARNING AND THE NOTION OF PLASTICITY" below in which we focus on principles of learning and development and domain-general skills. The following chapter (see section "WHAT EDUCATIONAL PROFESSIONALS NEED TO KNOW ABOUT NEUROSCIENCE") formulates a proposal as to the nature of the neuroscientific knowledge and insights which could be of use for educational professionals, and elaborates on the possible approach that is to be adopted.

BRAIN DEVELOPMENT, LEARNING AND THE NOTION OF PLASTICITY

The Brain as the Engine for Learning

Evolution has equipped the human brain with a number of important learning mechanisms that allow the individual to efficiently take in new information and adapt to the ever-changing environment (see Kolb and Whishaw, 2015; Kalat, 2018; Dehaene, 2020). For one, the brain is responsible for children's natural curiosity and exploratory behavior, which drives the development and organization of cognition and behavior in relation to environmental demands (Jolles, 2016, 2020). Furthermore, attentional mechanisms guide the orientation to stimuli in the physical, cognitive and the socio-emotional domain. They are responsible for amplifying important signals while discarding stimuli that are not relevant for current or future use (Dehaene, 2020). The selection that the brain makes is based upon past experience and evaluation of the possible future use. As such, the brain constantly makes predictions about what is going to happen and what would be the best way to act. Errors in such predictions are used to update mental models of the environment. Finally, the brain selects the stimuli that will be consolidated into memory for use at a later moment in time (see also Dehaene, 2020).

Information processing and the processes of attention and consolidation are quite well understood, and the neurochemical, neurobiological, and neurophysiological principles underlying it are currently handbook knowledge for students in the neurosciences and biological psychology (e.g., Kolb and Whishaw, 2015; Kalat, 2018). The same applies to the process of retrieval of stored information from memory. A broad understanding of the brain's attention, consolidation and retrieval processes is not only relevant for the remediation of patients with a neuropsychological dysfunction or brain disease (see Lezak et al., 2012) but also for application on children and adolescents in their development and schooling. Yet, it is important to take note of the biological and contextual factors that constrain these processes.

As the brain is part of our body and an organ in need of energy, nutrition and sensory stimulation, it is subject to metabolic constraints. Energy, nutrition and sensory information are therefore needed to ensure that the brain is in an optimal condition to learn (see also Thomas et al., 2019). So, when the brain functions sub optimally, it can experience problems in learning and attention which could manifest themselves in forgetting, lack of concentration, academic indifference or cognitive overload. Many contextual and internal factors have been found to impact optimal or suboptimal functioning of the brain (e.g., Lederbogen et al., 2011; Batenburg-Eddes and Jolles, 2013; Goddings et al., 2014; Miller and Halpern, 2014; Smith, 2018; Sharman et al., 2020) including: (lack of) sleep, fatigue, problems in energy supply, metabolic problems, puberty, sex differences, dietary intake, stress and/or major affective problems (mood problems, aggression, anxiety), use of alcohol and drugs, sensory under- or overstimulation, and developmental dysfunctions. Therefore, and because of their influence on brain functioning, these external and largely non-psychological factors can have a major impact on educational outcomes. This is the reason that researchers on the domain of MBE in past years have investigated educational interventions and learning performance in relation to contextual and supportive factors such as sleep (Sharman et al., 2020), the effect of nutritional interventions (Wurff et al., 2019), the impact of movement and physical exercise (Heppe et al., 2016; Reigal et al., 2020), mindfulness training (see Felver et al., 2016), action video game playing (Bediou et al., 2018), learning a musical instrument or a second language (Moreno et al., 2015; Benz et al., 2016), and others.

The notion behind educational interventions such as mentioned above is that the student should arrive in the learning situation *fit to learn*: be it listening to instruction in the classroom, working on homework assignments or exploring a museum. In other words, the brain should be in an optimal condition for information processing (see also Thomas et al., 2019). Interventions such as those mentioned here are thought to help in attaining this goal by stimulating active engagement, optimizing information processing, focusing attention and sustaining concentration. This enables the student to get more study motivation and improve in academic performance. According to leaders in the field, this type of neuroscience findings are potentially able to enrich theories of cognition and behavior. It is promising in this respect that new resources pertaining to neuroscience findings have become available to teachers in past years: online courses and books on topics related to brain function and development, and on behavior both in- and outside the classroom (e.g., Tokuhama-Espinosa, 2011; Steinberg, 2014, 2019; Tokuhama-Espinosa, 2014; Blakemore, 2018; Hohnen et al., 2019).

BOX 1 | Basic building blocks of the brain.
To better understand and appreciate the insights summarized in section "BRAIN DEVELOPMENT, LEARNING AND THE NOTION OF PLASTICITY," it is necessary to have a basic understanding of the "basic building blocks" of the brain and their development. For this, we would like to refer to a report by the Society for Neuroscience (SfN), formulating eight "*Neuroscience Core Concepts (The Essential Principles of Neuroscience)*" that one should know about the brain and nervous system, and have broad application for K-12 teachers and the general public (Society for Neuroscience, 2008; Note: K-12 means 'from Kindergarten to 12th grade and is an American expression which indicates the range of years of publicly supported primary and secondary education found in de United States). This text summarizes what every student – and of course their teacher – should know about neuroanatomy and the basic building units of the brain, and about its development and maturation. Briefly, everybody should know about the architecture of the brain and its basic constituents, the more than 90 billion neurons. *Neurons* are the nerve cells which underly brain function and eventually the biological functioning of the body, behavior, cognition and affect. Neurons have a cell body and several extensions, one of which is called the *axon*, through which the neuron sends electrical signals away from the cell body and others, called the *dendrites*, through which the neuron receives information from other neurons. The neurons communicate with each other via their axons and their connections on the dendrites and the cell body of other neurons. In the course of brain maturation, many nerve fibers eventually form highly interconnected *networks*. The points where nerve cells connect is called the *synapse*, and the *communication* between neurons takes place by biochemicals called *neurotransmitters*. The number of synaptic connections originating from one particular neuron can change in relation to experience and also the efficiency of the synaptic transmission can change. Being engaged in a complex neuronal network may lead to a situation in which the individual neuron eventually can have far more than 10.000 connections to other neurons.

The Development of the Brain

The development of the central nervous system starts already very early in the prenatal period, but major changes still take place in the micro- and macro architecture *after* birth. Both prenatal and postnatal development are subject to environmental influences. Of major importance in the postnatal period is the finetuning in the development of the *neuronal networks,* which connect the many regions in the brain cortex and structures deeper in the brain. This period is characterized especially by the major changes in connections between adjacent cells and the fine-tuning of connections within and between neuronal circuits.

The networks enable the brain to act like a symphony orchestra whereby individual regions in the brain can contribute to the total output by working together with other regions that have another task or role. In particular developmental periods – notably in early childhood and early adolescence – there is a burst in the number of synapses and connections that neurons make, followed by a period of elimination (called "*pruning*") of some of these connections and synapses. Synaptic plasticity (see section "Brain Plasticity Is the Key to Learning and Development") is thought to be one of the primary mechanisms by which the brain changes as a function of experience and which results in learning. Another mechanism is that of *myelin formation* in which particular bundles of axons become insulated by a specialized non-neuronal cell, and this results in faster electrical transmission over these fibers.

The maturation of the brain is thought to proceed up till well after the 20th year of life (Gogtay et al., 2004; Giedd, 2015; Dahl et al., 2018; Steinberg, 2019). The initial overgeneration of synapses and their elimination (synaptogenesis and synaptic pruning) are not uniform across the brain but they differ by regions. It appears that regions associated with basic motor and sensory functions undergo these developmental processes earlier in the period of childhood and adolescence than regions involved in higher-level functioning (to be described in par 3.6. in terms of Executive Functioning). Therefore, regions whose functions are heavily affected by experiences and new knowledge – and thus by learning and education – are relatively late to mature. This applies to regions within the prefrontal and parietal cortices and the neuronal networks which they are part of (e.g., Crone and Dahl, 2012; Blakemore, 2018). So, the various regions in the brain (and their connections) mature according to a different time scale.

Brain Plasticity Is the Key to Learning and Development

The brains of different people generally have the same large-scale organization which has evolved over the course of evolution. Yet, although the basic structure and functioning of the brain is influenced by genetic predispositions, there is a built-in flexibility in brain development. This allows the brain to adapt to its specific surroundings, thereby enhancing the chances of survival and optimal behavioral adjustment (Bjorklund, 2020; Dehaene, 2020). This built-in flexibility is called "plasticity," a key neurobiological process that refers to neural changes in response to experience and to specific characteristics of the (internal and external) environment. Plasticity allows the brain to reorganize after injury and to adjust to atypical environmental circumstances. Yet, plasticity is also key to typical development and learning at home and in school. The fact that the brain is able to change in response to environmental demands makes learning and education possible. This is essential for the individual to adapt to a changing environment.

It is relevant to distinguish between the so-called "experience-expectant plasticity" and "experience-dependent plasticity," as proposed by Greenough and colleagues in 1987. *Experience-expectant plasticity* refers to neural changes in response to experiences that are universal to all individuals within a species, such as changes related to the perception of light and sound. At birth, brain regions have a certain predisposition for specialized processing in a specific domain (e.g., visual or auditory perception, spatial processing, or language) by virtue of the cell types and connectivity patterns that these brain regions display (Dehaene, 2020). Yet, specialization will only occur if the individual receives the right kind of stimulation within a certain time frame of development. If the right input is not received, this will result in an abnormal pattern of neural organization (Greenough et al., 1987). At first sight, this may seem inefficient and even potentially harmful. Yet, this type of plasticity allows for greater flexibility in unusual circumstances, e.g., in case of sensory impairments such as blindness, while providing enough stability once the brain matures (e.g., Bedny et al., 2015).

In contrast, *experience-dependent plasticity* occurs in response to experiences that vary between members of a species, i.e., the culture in which the subject grows up or the skills they acquire in school or on the sports field. Examples are academic skills, such as learning how to read and do math, learning to appreciate literature, interests and activities in the domain of science and technology, playing football or studying the history of the country. Experience-dependent plasticity thus allows individuals to adapt to their unique environments by impacting the biological organization of the brain of the individual. Importantly, experience-dependent plasticity is not strictly age-dependent, allowing changes across the life span. Nevertheless, it is important to keep in mind that plasticity is generally greater early in life, and that early environmental influences may influence future developmental trajectories (Bjorklund, 2020). This explains how slight differences between individuals in their preference, information processing abilities, or contextual input at an early age may cascade into larger differences later on.

The examples show: *it is the context that shapes the brain* (Jolles, 2016). Whereas genetic predispositions are responsible for innate perceptual, cognitive or behavioral biases, the particular experiences and socio-cultural niche in which learners find themselves determine the way in which such biases are expressed and develop into more complex psychological mechanisms (Bjorklund, 2020). As such, the concept of Gene X Environment X Development interactions (cf. Bjorklund, 2020) is the essence of the learning process and of key importance to teachers, as they have the task to provide the optimal conditions for learning, and decide about the timing of instruction (Thomas and Knowland, 2009). Teaching and the pedagogical approach chosen by the teacher will enable their students to encode knowledge, make creative connections between different pieces of information, to acquire basic academic skills and to broaden their knowledge about the world.

Examples of How Experience Shapes the Brain

The brain reacts to environmental stimulation by an adaptation of its macro- and microarchitecture. In past decades, research evidence obtained in animals but also in human subjects has shown that the organization of complex neuronal networks in the brain can change in relation to sensory stimulation, execution of simple and complex motor acts, and other types of experience (e.g., Jolles and Crone, 2012; Ansari et al., 2017; Dehaene, 2020). As an example mentioned by Ansari et al. (2017): when one of the fingers is consistently stimulated more than the others, its representation in specialized structures on the brain cortex will eventually be enlarged relative to the cortical representation of the other fingers. Eventually, more neurons in a specialized region in the motor cortex will respond to the stimulated finger in comparison to the non-stimulated ones. Similar findings have been shown in the domain of music learning in string instrument players (e.g., Pantev et al., 2003). Other well-known examples are changes in brain structure in subjects who learn to juggle (Draganski et al., 2004) and in taxi drivers who learn to navigate complex spatial environments (Maguire et al., 2006). Furthermore, it has been shown how the brain changes in relation to learning to read, learning to do arithmetic, and learning other types of auditory, visual and language skills (see Dehaene, 2020 for elaboration and Ansari et al., 2017). Importantly, learning-related changes have not only been observed *within* individual brain regions, but also in the interactions *between* brain regions (e.g. Mackey et al., 2012, 2013; Jolles et al., 2016; see also Jolles et al., 2020). This is in line with the idea that functional specialization of brain circuits occurs through activity-dependent interaction and competition between different brain regions (Johnson, 2011). In this context, it is important to reiterate that experience-related changes in brain function and structure should be viewed form a developmental perspective, suggesting that experience-dependent plasticity is not necessarily the same for children, adolescents and adults (for a more extensive discussion of maturational changes in learning and plasticity, see Galvan, 2010; Johnson, 2011; Jolles and Crone, 2012). Finally, besides direct effects on neural processing within and between specific brain areas, experience may also have more general or indirect effects on brain function. Of particular interest in this respect is the effect of physical exercise, which appears to benefit cognitive functioning and wellbeing by inducing more broad neurobiological changes (for a review, see Mandolesi et al., 2018).

Psychological and Social Factors and the Brain

In recent years, new scientific knowledge has been obtained which shows that individual differences in children's socio-economic status (SES) and the environment in which a child grows up affect the organization of the human brain (Hackman et al., 2010; Ansari, 2012; Farah, 2018; see also Rindermann and Baumeister, 2015). As an example, Lederbogen et al. (2011) showed that the brain's response to stress was different in individuals growing up in urban environments versus those growing up in rural environments. There is now strong evidence that the brains of children growing up in environments that do not supply the proper sensory, cognitive or social-emotional stimulation develop differently from those of their peers who grow up in more "enriched" environments. Several papers have been published which make this point in a comparison of children growing up in families from a lower versus higher SES (e.g., Mackes et al., 2020; see also Farah, 2018). As an example, Khundrakpam et al. (2019) found non-linear effects of socioeconomic status on brain development in childhood and adolescence with associations between parental occupation, cortical thickness and language skills. In adolescence, social isolation appeared to disrupt cortical development and goal-dependent decision making (Hinton et al., 2019). Likewise, both brain structural and functional changes were apparent in adolescents in the context of alcohol abuse (Jadhav and Boutrel, 2019). It has been concluded that brain maturation is negatively affected by poverty (see Noble, 2017; Davis, 2020). The findings from a rapidly increasing number of research articles thereby underscore the vision that the social environment is very important, and – in relation to the many findings about brain plasticity (see section "Brain Plasticity Is the Key to Learning and Development") – the notion that *context shapes the brain*. It is of interest that similar findings had already been done in the fifties and sixties in rodents. These investigations showed that rats that were reared in impoverished environments had smaller brains than rats who were reared under enriched conditions (see textbooks such as Kalat, 2018 and Gray and Bjorklund, 2018).

In the context of education, it is of importance to note the large literature on possible sex differences in cognitive performance and the question as to whether differences are due to biological factors or to culture and the social environment. Strong indications exist that both biological and social/cultural factors play their role. This implies that the differences in cognitive performance which have been reported in the many scientific articles which are based upon crosssectional research can*not* be ascribed to inborn mechanisms *per se*. Accordingly, Miller and Halpern (2014) in their authoritative review on "the new science of cognitive sex differences" elaborated upon the important role of upbringing and cultural factors such as economic prosperity and gender equity, but also on brain factors and the role of prenatal androgens. With respect to differences in brain structure, Lenroot and Giedd (2010) showed that adolescent males and females exhibit a four years difference in the age at which their brains reach the greatest volume (the average age is 10.5 years for females and 14.5 years for males). Thich implies that the brain maturation of males lags behind that of females in the period of early and middle adolescence (see also Gur and Gur, 2016). The notion that brain maturation of boys and girls follows another timescale receives support from other investigations (see Miller and Halpern, 2014; Giedd, 2015; Choleris et al., 2018; van der Graaff et al., 2018; van Tetering et al., 2018; Wierenga et al., 2018). Such a maturational gap is thought to make the brain development of boys and girls differentially vulnerable to upbringing and the influence of their environment – which is different for the majority of boys and girls from birth on (Miller and Halpern, 2014; Jolles, 2016, Jolles, 2020). This explains findings such as those reported by Barbu et al. (2015). These authors studied sex differences in language acquisition across early childhood and found that family socioeconomic status does not impact boys and girls equally. Likewise, the sex differences in self-regulation in adolescents which we recently found in a large-scale cross-sectional study could be ascribed to the major influence which social factors have on brain maturation (van Tetering et al., 2020). Taken together, boy-girl differences in cognitive performance and academic achievement are due to a complex interplay between biological and psychosocial factors. It is thus of importance to understand how biological and environmental factors interact and, as Miller and Halpern (2014) put it "in order to maximize cognitive potential and address pressing societal issues."

The findings are of major importance for the domain of education. This is because of the challenges that teachers encounter in their educational interactions with boys and girls, with students who have another cultural background, and those who differ in socio-economic factors and the financial possibilities of their parents (e.g., Rindermann and Baumeister, 2015). More research is needed, but the studies which have been performed up till now do suggest that personal life- and learning experiences and culture are an important factor that impacts neuropsychological functioning. While education plays an important role in passing on cultural norms and values, there are also cultural differences in the way education is organized (see Downey et al., 2019). Cross-cultural research suggests that this may influence the development of cognitive and academic skills, including executive functioning (e.g., Ellefson et al., 2017; Xu et al., 2020). Taken together, it is probable that these socio-cultural factors impact the extent to which the developing child has been stimulated on the physical, the cognitive, the social and the emotional domain (Jolles, 2016), leading to differences in brain function across children from a different background. The extent to which specific cultural and economic factors impact brain development is an important direction of future research.

Childhood, Adolescence, and Emerging Adulthood

Throughout the past decades there has been a significant amount of scientific investigation into brain development across childhood and adolescence (see Crone and Dahl, 2012; Sheridan and McLaughlin, 2014; Fuhrmann et al., 2015; Blakemore, 2018; Dahl et al., 2018). As described in **Box 1**, research shows that various brain regions display a different developmental trajectory, with regions in the temporal and frontal lobes the last to mature. Knowledge of these regional trajectories offers insights into the developmental timing of emerging skills related to decision-making, perspective taking, self-regulation, and other major cognitive and affective functions (e.g., Crone and Dahl, 2012; Mills et al., 2014; van Tetering and Jolles, 2017; van Tetering et al., 2020; see also the paragraphs on Executive Functioning later in this chapter). A number of important changes take place during adolescence, a distinct developmental period characterized by rapid growth, hormonal and metabolic changes, specific neuro-maturational changes, as well as changes in social and cultural responsibilities (Crone and Dahl, 2012; Blakemore and Mills, 2014; Dahl et al., 2018; Steinberg, 2019). Growing evidence points to a particular importance of changes in social and affective processing during adolescence (e.g., Larsen and Luna, 2018). Importantly, insights about changes in sensitivity to the peer group and social rewards are crucial for understanding adolescent vulnerabilities such as the high rates of risk-taking and substance use (Knoll et al., 2015; Romer et al., 2017; Smith, 2018). Yet, adolescence is also a window of opportunity for social and emotional learning, and making a positive impact on societal problems (UNICEF, 2017; Dahl et al., 2018). It is becoming acknowledged that the adolescent brain is a social brain (Crone and Dahl, 2012; Blakemore and Mills, 2014; Blakemore, 2018), which is open to novelty and exploration, and thus for knowledge acquisition and learning new skills (Batenburg-Eddes and Jolles, 2013; Fuhrmann et al., 2015; Jolles, 2016). This makes learning an important target for interventions not only on the domain of cognitive performance but also – and especially – that of social and emotional learning (Blakemore, 2018). Therefore, the evidence pointing to the prolonged brain and neuropsychological development across adolescence has a profound influence on the way in which we now think about the teens who traverse this important phase.

The period of adolescence is thought to last from around 10 years of age to the mid-twenties (e.g., Steinberg, 2014, 2019; see also Crone and Dahl, 2012). While the beginning of adolescence is clearly marked by the onset of puberty, the end of adolescence is less clear (Giedd, 2015; Dahl et al., 2018). Late adolescence overlaps with adulthood in the phase of "emerging adulthood." As proposed by Jeffrey Arnett (2000), this is an important period of development, in which the brain is still in a process of maturation, albeit less pronounced than before. Studies in which brain structure was measured by MRI, reveal that the brain continues to change in structure through emerging adulthood (Gogtay et al., 2004; Houston et al., 2014; Giedd, 2015; Galvan, 2017). Furthermore, emerging adulthood is a phase during which individuals gain important experiences related to the formation of their identity and "personal growth" (Hochberg and Konner, 2020). Therefore, it is now established that the human brain is not fully developed by the time individuals reach culturally defined adulthood – at the 18th birthday in many western countries. Experts in the field propose that individuals in their late adolescence and early adulthood sometimes do not yet have the skills, the attitudes and experience they need to act as an independent and well-functioning member of the adult society (Hochberg and Konner, 2020).

Executive Functioning

In past years, we have gained much insight in a particular set of neuropsychological skills that function across cognitive domains and which are considered an essential prerequisite for learning and our adaptation to a changing environment. These so-called "Executive Functions" (EF's) are a set of cognitive and non-cognitive processes that determine which sensory stimuli are selected and how information is processed, encoded and retrieved. They are essential for learning and have – over the past decade - received much interest from the educational domain (Jolles, 2016, 2020). Three important fundamental processes which are nowadays shared under the umbrella of the EF's are working memory, inhibitory control and cognitive flexibility (Diamond, 2013). *Working memory* refers to the ability to hold information in a temporary storage while operating on it, whereas *inhibitory control* is the ability to inhibit responses and select among different stimuli that are present. *Cognitive flexibility* refers to the ability to switch back and forth between different tasks or perspectives (Diamond, 2013). The construct of EF shows overlap with different aspects of attention, including *focused attention*, which describes the ability to focus upon a particular stimulus while ignoring or inhibiting other types of information, and sustained attention, which refers to the skill of staying in a state of concentration for a prolonged period of time. Together, these basic neurocognitive functions enable the individual to engage with the material which has to be learned, to hold it in mind, operate upon it, and select the relevant information while at the same time inhibiting information that will not inform their understanding, but rather interfere with it.

The three fundamental EFs are controlled by higher order cognitive and non-cognitive functions or skills. As Adele Diamond (2013), an expert on the field of developmental cognitive neuroscience put it: "*Executive functions refer to a family of top-down mental processes needed when you have to concentrate and pay attention, when going on automatic or relying on instinct or intuition would be ill-advised, insufficient, or impossible.*" The EFs give us the time to think and not to act too quickly and enable us "to play with ideas." They help us to engage in new, unexpected challenges, to resist temptations and to monitor the route to the goals we have formulated (Jolles, 2016; van Tetering and Jolles, 2017; van Tetering et al., 2020). When considering EFs in the broadest sense of the word, other relevant skills that fall under the umbrella of the EFs include self-insight and self-regulation, social monitoring, emotional processing and empathy, planning and prioritizing, overseeing the consequences of one's actions and insights into other person's intentions and the roles played in social and cultural contexts (Lezak et al., 2012; McCloskey and Perkins, 2013; Dekker et al., 2016; Jolles, 2016, 2020; Chen et al., 2018). The EFs play a key role in the evaluation of the emotional and motivational value of stimuli and they enable the individual to make plans for the short and long term, to prioritize and select the optimal route to attain goals and to be creative (Lilly, 2020). They enable the individual to evaluate or judge his or her position in relation to others, to the group and the social system and to act according to this evaluation. Therefore, the EFs are not only relevant for cognitive performance but also for self-regulation and behavior, and for social and emotional functioning. They are indispensable for personal growth over the period of childhood and adolescence.

Therefore, it goes without saying that the EFs are important for education. The EFs may help teachers to better understand students in their classroom, their behaviors and individual differences therein (e.g., Dawson and Guare, 2018). For effective teaching, teachers must be aware of how to get their students' attention, how to inspire them and how to support the self-insight and self-regulation which are needed for study motivation and academic achievement. Teachers should have the tools and experience to alert their students, help them select the most relevant information, resist distraction, and encourage them to keep on task (i.e., to sustain their attention). Furthermore, teachers should have the know-how to help their students organize and prioritize in task execution and planning, and to support personal growth. Educators should therefore be aware of the existence of the EF and the role they play in learning and performance.

Development and Training of the Executive Functions

Brain networks underlying EFs involve various substructures in de prefrontal cortex, in the parietal lobe, the limbic system and various subcortical regions which change over the course of an individual's development (Morton, 2010; Larsen and Luna, 2018). The most fundamental EFs including the attentional processes and the ability to hold a select number of items in working memory start to develop already in very young children. The more complex processes, such as inhibitory control and the manipulation of information in working memory, develop over the whole period of childhood and adolescence (Hoeschler et al., 2018). Furthermore, higher-order cognitive and non-cognitive EF mature even through emergent adulthood in the third decade of life (e.g., Dahl et al., 2018; Steinberg, 2019). In the context of adolescence as the period in which the social brain develops it is not surprising that the non-cognitive aspects of EF become particularly important during this phase of life. The prolonged development of EFs makes these functions an important target for educational interventions (Thomas and Knowland, 2009; van Tetering and Jolles, 2017; van Tetering et al., 2020). Moreover, the finding that EFs differ between children depending on their cultural environment (e.g., Ellefson et al., 2017; Xu et al., 2020) suggests that these skills are changeable and plastic, and potentially trainable (Diamond and Ling, 2016, 2020; García-Madruga et al., 2016; Rice, 2016). This is also apparent from intervention studies showing that EFs can be remedied in children raised in deprived home environments (Neville et al., 2013). As the EFs are domain-general skills important to virtually all academic domains, it has been argued that targeting the EFs may have broad effects on academic development (Thomas and Knowland, 2009). Yet, more research is needed to find the most optimal ways to train EFs and potential moderating factors. At present, most training programs focusing on basic EFs show only limited transfer beyond the skills that are trained (Simons et al., 2016; Gathercole et al., 2019). Programs targeting higher-order EFs, notably self-regulation may have more potential in that respect (Poon, 2018; Xue et al., 2018: see also van Tetering and Jolles, 2017; van Tetering et al., 2020).

WHAT EDUCATIONAL PROFESSIONALS NEED TO KNOW ABOUT NEUROSCIENCE

Where Do We Stand?

The OECD stated its influential report "*Understanding the brain. The birth of a learning science*" (2007) that the time is ripe to use knowledge and insights about brain, cognition and behavior on the educational domain. Nowadays, fifteen years later, the field of MBE is still considered to be "promising" in its possible contribution to educational innovations. However, there is not yet a converging view on the nature of the knowledge and insights into brain and brain functioning which might have relevance for education. Accordingly, it is not clear what the best approach could be to educate the educator in this respect. An important reason may be that present insights into the basic architecture and mechanisms of brain and mind are huge and diverse. This makes transfer difficult: the knowledge is distributed over more than 40 neurodisciplines and over the fields of cognitive science, psychology and pedagogy. In addition, there has not yet been enough interaction between educators and educational scientists on the one hand and the various representatives of the neurosciences, the cognitive and behavioral sciences on the other.

As described in this article and in other papers on "the promise of the neurosciences for education," the results from brain imaging research are considered to be very interesting and to have potential to contribute to our understanding of the mechanisms underlying activities such as language acquisition, reading, arithmetic and many cognitive functions and processes. However, the brain imaging findings as such are, generally, not able to provide the insights and predictions that the field of education needs on a day-to-day basis. There are very few examples of insights from brain imaging research that will directly contribute to innovations in didactics or teaching or provide guidance for the type of decisions that the teacher has to make in class. Yet, there is other neuroscientific knowledge that could be relevant for application in the educational domain: neuroscientific knowledge and insights could support teachers in their pedagogical approach by broadening our insights into the mechanisms of learning and the learning individual. The insights in brain plasticity and the factors which impact the optimal functioning of the brain may help to formulate answers to important questions like "what are the factors that determine the selection, consolidation and retrieval of environmental stimuli?", "how does the brain learn from errors, and what is the role of surprise?", "what external factors determine the efficiency of information processing?", and "what are the optimal conditions for learning?", as well as "how does the brain develop and mature over the long period from early childhood through emergent adulthood?", and "how do educators (teachers, parents) influence that process?". These issues about the brain are relevant for every educator.

On Issues About the Brain That Every Educator Should Know

Section "BRAIN DEVELOPMENT, LEARNING AND THE NOTION OF PLASTICITY" of this article gives an introduction into the important theme of "plasticity" which is an inherent property of the brain that enables us to adapt to the ever-changing environment, and about the basic building blocks of the brain which underly plasticity (**Box 1**). "Experience-dependent brain plasticity" was described as the key process when the learning individual consumes new information and consolidates this into the brain hardware (i.e., in the extremely extended system of synaptic connections that make up large-scale brain networks). Complex information from the sensory, cognitive, social and emotional domain – i.e., the environment – interacts with genetically defined predispositions, and together they are responsible for brain development and learning. This underscores the notion that teachers, parents and other educators are important, even essential, for personal development. Educators create the conditions for the acquisition of knowledge and experiences that are to be stored by the learning brain and they inspire and direct the process of curiosity and information processing by the student (Jolles, 2016, 2020).

Specific attention should be paid to the executive functions. The most fundamental components of executive functions, including certain attentional and inhibition processes, start to develop already in early childhood. Yet, more complex EF abilities, notably self-insight and self-regulation, but also empathy, social monitoring, mental manipulation, cognitive flexibility, planning and problem solving, develop over the long period of childhood and adolescence – provided that the environment gives the support and inspiration that the learning person needs. In this respect, it is of major importance for the educational field to know that brain maturation extends through early, middle and late adulthood and toward the 23rd to 25th year of life. The major EF still develop, even in emerging adulthood. This reflects itself in the personal growth of the learning person, which enables him or her to take an independent position in society.

Four Key Issues About the Brain

Based upon the accumulating insights described in preceding paragraphs, we will now describe four issues that – in our opinion – are to be regarded as essential knowledge for educators and which should be part of any teaching program for aspiring teachers and for continuous education. It is our conviction that knowledge of these issues will impact teaching and the pedagogical approach to the learning individual, and their development and personal growth. These four major issues around brain structure and neuropsychological functioning follow the eight "Neuroscience Core Concepts" ("The essential principles of Neuroscience"), which have been formulated by the Society for Neuroscience (Society for Neuroscience, 2008) and introduced in **Box 1**. These Core Concepts "offer fundamental principles that one should know about the brain and nervous system" (Society for Neuroscience, 2008). According to the SfN, the Neuroscience Core Concepts "have broad application for K-12 teachers and the general public, offering the most important insights gained through decades of brain research".

The core concepts have to do with the four overarching insights that: (1) "The nervous system controls and responds to body functions and directs behavior"; (2) "Nervous system structure and function are determined by both genes and environment throughout life"; (3) "The brain is the foundation of the mind", which includes cognitive, social and affective functioning; (4) "Research leads to understanding that is essential for development of interventions for the active stimulation of optimal brain function and therapies for nervous system dysfunction." Note that the last statement was slightly adapted by the current authors to include the pursuit for optimal brain functioning in healthy individuals. Embedded in the four mega-concepts, are insights such as "the human brain endows us with a natural curiosity to understand how the world works" and "intelligence arises as the brain reasons, plans, and solves problems," "life experiences change the nervous system" and quite some others which lie at the core of the issues described in the present article. We propose that the neuroscience core concepts formulated by the SfN could be a valuable starting point for any undertaking directed at "educating the educator" about the student and the learning brain. We consider this essential knowledge to be taught to both pre-service teachers and in-service teachers and other professionals in the educational domain. **Box 2** goes in depth as to knowledge and insights that should be part of any undertaking at educating the educator about the brain (note that **Box 1** confines itself to the description of the basic building blocks of the brain, i.e., neuroanatomical issues).

BOX 2 | Themes about brain functioning which should be part of the knowledge base of educators.
It is of importance for the educational professional to have a basic insight into brain plasticity and brain development and into major aspects of human information processing. Textbooks for undergraduate students in psychology/behavioral science (e.g., "Introduction into Biological Psychology" Kolb and Whishaw, 2015; Gray and Bjorklund, 2018; and Kalat, 2018) may provide a good starting point. The four themes described below give a compact description of the issues which could be relevant in this respect. These topics are based on the "Neuroscience Core Concepts," formulated by the Society for Neuroscience (Society for Neuroscience, 2008).

Theme 1. "The nervous system controls and responds to body functions and directs behavior."

*This theme includes basic knowledge about the anatomy and functions of the nervous system (see also **Box 1**). Key topics include*:

The micro-anatomy of the nervous system: cells, dendrites, axons, spines, glial cells, myelin, neurotransmitters, neurohormones. The macro-anatomy of the nervous system: hemispheres, neocortex, gray and white matter, cerebellum, basal ganglia, limbic system, thalamus and hypothalamus, brainstem and ascending/descending fiber system, blood supply of the brain. Neurophysiology, impulse propagation, synaptic transmission. The input and output systems: senses and incoming information; the peripheral nervous system, innervation of the muscles, endocrine glands and internal organs.

Theme 2. "Nervous system structure and function are determined by genes and environment throughout life."

This theme concerns issues related to brain development and the influence of experience. Key topics include:

Brain plasticity. Brain development and maturation. Sensory circuits bring information to the nervous system whereas motor circuits send information to muscles and glands. Synaptic pruning. Development of child and adolescent through emergent adulthood. Sexual development. Individual differences. Organization of information processing, selection of stimuli, consolidation and retrieval. Natural curiosity and adaptation to a changing environment. Experiences change the brain. Lifelong changes in neuronal circuitry in relation to acquired knowledge and experiences.

Theme 3. "The brain is the foundation of the mind."

This theme concerns knowledge from the fields of cognitive (neuro)science and neuropsychology. Key topics include:

Basic functions of the brain: motor function, impulse control and cognitive flexibility, sensory systems, perception, attentional functions and concentration, memory, learning and forgetting, language. Executive functioning: self-insight, self-regulation, social monitoring, emotional processing and empathy, anticipation of future actions, planning, prioritizing and problem solving. Higher functions and neuropsychological processes: intelligence, reasoning and thinking, identity formation, communication, motivational processes, curiosity, and imagination.

Theme 4: "Research leads to understanding that is essential for development of therapies for nervous system dysfunction and helps improve the circumstances under which people learn."

This theme involves a basic understanding of neuroscientific research methodology and scientific discovery. Key topics include:

A basic understanding of the different disciplines within neuroscience, as well as other fields that intersect with neuroscience. The levels of analysis. Basic knowledge about methods used in brain and neuropsychological research in humans, notably Magnetic Resonance Imaging, EEG techniques, controlled experiments and quasi-experimental designs, epidemiological studies. Individual differences and external factors with impact on brain function: sleep, fatigue, nutritional factors, movement and exercise, risk factors and protecting factors for successful, normal or subnormal development, effects of training, emotional support and inspiration. Conditions: giftedness, developmental dysfunction, AD(H)D, autism and related disorders, learning problems, dyslexia, dyscalculia, language dysfunction, non-verbal learning disorder, stress, anxiety or mood dysfunction, addiction (alcohol, drugs), aggression.

Toward a Curriculum on Neuroscience Education for Educators

The description of "the neuroscience issues that every educator should know" (see section "Four Key Issues About the Brain" and **Box 2**) is a proposal on content, not on approach. It is quite an undertaking to make a translation from key issues and core concepts (**Box 2**, Society for Neuroscience, 2008) such as described in the present paper into a curriculum. There is only a limited amount of scientific information available on the effects of application of neuroeducation on the educational practice or attitudes and approach of teachers. A recent review on the results of neuroscience training for teachers in Trends in Neuroscience and Education, TiNE; Privitera, 2021) found only ten papers in which the description of the neuroscience courses used was of sufficient detail and quality to enable a comprehensive evaluation of the current research on neuroscience training for teachers. The authors of the TiNE paper found most results to be "promising" although there were quite some differences in the nature of the courses given, their contents, length, approach and the relative time spent on the various issues. The paper therefore supports the notion put forward in the present review, namely that the field is in need of a clear knowledge base on the scientific insights that the field of education needs. With the present article and especially with our proposal in chapter 4, we hope to provide a starting point for discussion among professionals from the fields of neuroscience, cognitive and behavioral science and professionals from the applied field of education, notably teacher trainers.

A stumbling block as to the organization of practical courses on neuroeducation is that up till now, there is only limited access to scientific literature, tools and written sources such as books, and courses aimed at teachers and other educational professionals. Moreover, accessible sources on the basics of Mind, Brain and Education science with both scientific knowledge and recommendations for educational practice are still very limited. An additional problem is that many sources are not yet based upon evidence-based or evidence-informed interventions in the educational setting. Yet, valid literature about the structure and functioning of the brain and about neuropsychological development does exist. This type of information can be found in textbooks which are written for undergraduate students in psychology. Examples are books such as "Introduction into Biological Psychology" (e.g., Kalat, 2018) and introductory texts in Neuropsychology (e.g., Kolb and Whishaw, 2015) and Developmental Cognitive Neuroscience (e.g., Goswami, 2019 or Blakemore, 2018). The advantage of these books is that they do not delve deeper in brain mechanisms and structure than is needed for an understanding of cognition, affect and behavior in relation to brain function, and that they have been used successfully for many years in major universities around the globe. The use of these well-written books has an additional advantage in that there are many examples of existing courses which are based upon these books. This makes it easier to make a new course for (pre-service or in-service) teachers in which existing examples of successful courses can be used to decide upon the nature and the volume of the to-be-learnt material. These basic books can be complemented with more specialized information. See **Box 3** with a list of easily accessible books on topics as reviewed in the present paper. One of the earlier accessible books was *The learning brain* by Blakemore and Frith (2005). These authors already stated that a shared vocabulary is needed between neuroscientists and educators. In the past decade, some books have appeared that do make a translation of neuroscience content or insights about Executive Functioning to the classroom. Recent books on the translation of neuroscience insights to the classroom are those by Tokuhama-Espinosa, 2014; Dawson and Guare, 2018; Hohnen et al., 2019). In addition to that, accessible books on the adolescent and his or her development are those by Steinberg (2014, 2019); these books provide important information on the adolescent and "the age of opportunity" with implications for pedagogical approach and attitude.

BOX 3 | Textbooks on the learning brain and the developing child and adolescent.

The books and literature which are described in this box are easily accessible and are "suggested reading" for educational professionals who wish to increase their knowledge and insights into the developing child and adolescent, learning and cognition. The full reference with bibliographical details can be found in the reference list.

Blakemore, S.-J., and Frith, U. (2005). *The learning brain. Lessons for education*.

Bjorklund, D. F. (2020). *Child Development in Evolutionary Perspective*.

Blakemore, S.-J. (2018). *Inventing ourselves: The secret life of the teenage brain*.

Dawson, P. and Guare, R. (2018). *Executive Skills in Children and Adolescents*.

Dehaene, S. (2020). *How We Learn: The New Science of Education and the Brain*.

Galvan, A. (2017). The Neuroscience of Adolescence.

Goswami, U., (2019). *Cognitive Development and Cognitive Neuroscience: the developing Brain*.

Gray, P., and Bjorklund, D.F. (2018). *Psychology*.

Hohnen, B., et al. (2019). *The incredible teenage brain: Everything you need to unlock your teen's potential*

Jolles, J. (2016). *The teen brain. On the adolescent between biology and environment (in Dutch)*.

Jolles, J. (2020). *Learning to know your child. On development, learning, thinking and the brain (in Dutch).*

Kalat, J.W. (2018). *Biological Psychology*.

Kolb, B., and Whishaw, I.Q. (2015). *Fundamentals of Human Neuropsychology* 7th ed.

Steinberg, L. (2014). *Age of Opportunity. Lessons from the New Science of Adolescence*

Steinberg, L. (2019). *Adolescence*.

Thomas, M. S. C., et al. (2020). *Educational Neuroscience: Development Across the Lifespan.*

Tokuhama-Espinosa, T. (2011). *Mind, Brain, And Education Science: A Comprehensive Guide To The New Brain-Based Teaching.*

Tokuhama-Espinosa (2014). *Making Classrooms Better*.

Essential for Educational Innovation: A Transdisciplinary Approach

It is imperative that curricula for educational professionals are developed from a multidisciplinary and multidimensional angle and that they are based upon a transdisciplinary attitude. Teacher trainers have an important role in that respect because they are specialists who have a vision about what the educational professional should know and why. They are also important to support teachers to become neuroscientifically literate as defined in the introduction of this article: they can help to further development of neuroscience literacy as a concept that demands for competence on reflective assessment of knowledge and to stimulate teachers to adopt a critical-reflective teaching method (e.g., Bergmann et al., 2017). Experts in the neurosciences and the cognitive and behavioral science contribute by proposing the relevant content from their domains, whereas specialists in neuropsychological development and cognitive performance are needed to contribute by giving directions about (sources of) individual differences, about factors contributing to the efficiency of information processing and about interventions that have proven effectiveness in the intervention of individuals with a cognitive dysfunction or a brain disorder.

In conclusion, what is needed is a translation and integration of knowledge that transcends the boundaries of the various domains, leading to a holistic or "transdisciplinary" approach to the study of learning and education. Transdisciplinary academic networks in which universities make formal collaborations with schools and institutes which are responsible for teacher training are useful in this respect. Such networks could stimulate the constructive dialog between disciplines and support individuals from various backgrounds to address educational innovations. International organizations such as the International Mind, Brain and Education Society (IMBES) and The European Association for Research on Learning and Instruction (EARLI) are vital for information exchange and collaborations on a higher level. In addition, a major role is to be played by specialists in science communication and experts in the use of the internet and social media. Special reports by international organizations like the DANA foundation, the Education Endowment Foundation, the Jacobs Foundation and the Society for Neuroscience and others could also play an important role.

CONCLUDING REMARKS

The present article suggests that there is some lack of progress on the topic of neuroeducation which has to do with three major factors. In the first place, research in the past fifteen years has placed the emphasis on the results of experiments in which brain imaging methods (notably Magnetic Resonance Imaging, MRI) have been used. In retrospect, the neuroimaging experiments have yielded interesting scientific results, which have deepened our understanding of brain mechanisms underlying cognitive and affective processes. Yet, the fundamental and unidimensional nature of most imaging studies prevents a direct application to the field of education. Future research should take a transdisciplinary approach to take on problems and questions *from the field of education*, investigating the same issue on multiple levels of analysis. Thereby, neuroimaging research, laboratory studies with well-controlled behavioral tasks, and classroom studies could mutually inform and constrain one another. Still, at present, there is relevant knowledge about the learning brain, which appears to lie in an improved understanding of how to bring the brain in an optimal condition to learn, and by stimulating insight into external, non-psychological factors which act upon the learning individual. The vast amount of knowledge about "brain plasticity" and related topics yields predictions that could help to optimize the conditions for information processing and learning. Educational interventions in which sleep and fatigue, nutritional status, attentional processes or movement are manipulated are examples of approaches that may prove of value and deserve the attention of educational professionals. Nonetheless, we would like to re-emphasize that neuroscientific insights need to be combined with insights from other domains to form hypotheses about learning in the daily context. Educational researchers may play an important role in testing these hypotheses, enabling the conversion of true scientific insights into scalable practical applications.

In the second place, there is a major lack of valid sources of information (books, articles, courses, internet sources etc.) for use by the interested educator. The fact that neuromyths are still prevalent (Dekker et al., 2012; Howard-Jones, 2014; Macdonald et al., 2017) and the seductive allure of neuroscience as well as our expectations about the contributions of brain training techniques (too optimistic) underscore our plea for the development of a curriculum for educators which makes use of valid sources which can be trusted. We suggested to use existing handbooks and textbooks on the domain of biological psychology and neuropsychology that are already in use for university students in the behavioral sciences.

In the third place, there is a substantial confusion of tongues with respect to the potential importance of neuroscience and cognitive science knowledge and insights. This is evident in opinions that are expressed in statements such as "a bridge too far," "beware of the brain hype" and visions stating that teachers do not need anything more than a good behavioral observation. To present an analogy with the applied field of health and disease: it is unthinkable that a medical practitioner or health care psychologist would have *no* knowledge about biology, about the structure and functioning of the heart, the digestive system, the brain and other organs and about the internal and external factors which determine functioning of the individual (see also Thomas, 2013). We are convinced that this also applies for the educational professional. Knowledge about the brain and its development and maturation, and about the factors which are responsible for normal, subnormal and successful learning can provide a context for a better understanding of behavior.

We feel that the criticisms related to the pretenses of cognitive neuroscience research are understandable. A statement arguing that "*we currently do not know enough about the brain to provide concrete recommendations for didactics and teaching*" is fair, as has been explained in this paper. It is indeed not possible to translate neuroscience insights directly into innovative didactics and educational interventions. However, apart from prescription about teaching, there is conceptual knowledge about the interplay between mind, brain and education. This knowledge is useful for teachers, as it could help them to contextualize children's behavior, inspire them, and/or assist them in making educational decisions and support their pedagogy. Another negative opinion about the relevance of neuroscience is that "*teachers know best how to interact with their students and that they should not lose their autonomy*." This notion is understandable because scientific research has provided general insights, which are not directly applicable to student A or student B. Notwithstanding that fact, the neuroscientific insights will hopefully give teachers more rather than less autonomy, as these insights could help them make more informed decisions (Dehaene, 2020), while staying true to their personal educational goals. Neuroscience is just one piece of the complicated puzzle of learning and education.

In sum, many of the remarks on the pretenses of the neurosciences and their possible impact for the field of education are understandable. They point to a confusion of tongues between disciplines. This implies that we should seek to stimulate the dialog and use a translational approach. In that respect, it is of importance to change the attitude of the various disciplines and participants and promote a mutual respect for the knowledge, insights and methods of other disciplines. This means: respect for the representatives from other disciplines and helping each other to acknowledge the existence of a language gap which can lead to stumbling blocks and lack of progress. We plead for a collaboration between the various fields, in analogy to the collaboration between the fundamental and applied disciplines in the multidimensional field "health and disease." The implications are, that it is essential to come to a reorientation of knowing and knowledge, insights and science. We have to change our attitude and come to a multidimensional and multidisciplinary approach in educational innovation. Scientific insights into learning, about the learning brain and about factors that are responsible for normal, successful and suboptimal learning can help the educational professional to create the optimal conditions for talent development in his students.

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Looking for the Brain Inside the Initial Teacher Training and Outreach Books in Portugal

Joana R. Rato*, Jorge Amorim and Alexandre Castro-Caldas*

Centre for Interdisciplinary Research in Health, Institute of Health Sciences, Universidade Católica Portuguesa, Lisbon, Portugal

The fascination with brain research is widespread, and school teachers are no exception. This growing interest, usually noticed by the increased supply of short-term training or books on how to turn the brain more efficient, leads us to think about their basic training and outreach resources available. Little is known about what the official Initial Teacher Training (ITT) offers concerning the brain literature and if it meets scientific standards. Also, what are the science communication materials that teachers can access to learn about the developing brain remain undiscussed. First, we examined the ITT courses taught in Portuguese Higher Education, both in public and private institutions, to identify the syllabus with updated neuroscientific knowledge. Second, we searched for the neuroscience-related books published in the last 6 years through the National Library of Portugal database. Thirty ITT courses and 35 outreach publications were reviewed through a rapid review methodology. Our results showed an absence of curricular units indicating in their programs that brain research, and its relationship with learning, would be taught in a representative and updated way. In contrast, the number of brain-related books for educators increased in Portugal, corroborating the demand for this field of study by these professionals. Based on the literature that shows how misunderstandings about the brain have increased in school contexts, our discussion recognizes that science outreach could be a way to increase the scientific literacy of school teachers with the research community working more in this direction, but, since a previous problem seems to be unsolved, there is an urgent need for specialized attention to the development of training curricula for future kindergarten and elementary school teachers.

Keywords: syllabus, teacher training courses, neuroscience education, outreach books, mind, brain, and education, rapid review

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Valeria Abusamra, University of Buenos Aires, Argentina

Reviewed by:
Vitor Teodoro, Lusophone University of Humanities and Technologies, Portugal
Yesica Aydmune, CONICET Institute of Basic, Applied and Technology Psychology (IPSIBAT), Argentina

****Correspondence:***
Joana R. Rato
joana.rato@ucp.pt
Alexandre Castro-Caldas
acastrocaldas@ucp.pt

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INTRODUCTION

In the educational neuroscience field, which has been advancing more to emerge as a distinct discipline, how to integrate neuroscience into educational practice remains a discussion (Wilcox et al., 2021). Between the past (or still present) caution views and promising research works arising, all agree that more is needed to build a robust translational bridge between brain research and classroom practices (e.g., Bruer, 1997, 2006; Ansari and Coch, 2006; Kelleher and Whitman, 2018; Tan and Amiel, 2019).

One of the problems pointed on this highly interdisciplinary research framework is based on the scarce specialty literature. It has been presenting more discussion about the promise of applying neuroscience to education than educational neuroscience applications already studied (Bruer, 2016). Increasing the evidence-based practice (EBP) rate in school contexts is a pre-occupation in the educational sciences since the 1990s (Davies, 1999). Despite the growing of EBP potential recognition to transform teaching and learning, incorporating collaborative research projects into everyday school practice has not been seen by the teachers as so easy as expected (Walker et al., 2019).

The relationship between neuroscience and education advances theoretically but not practically in natural contexts (Thomas et al., 2019), and we still found an ongoing debate about the potential of interdisciplinary research and its applications. Several societies and special interest groups established being the International Mind, Brain and Education Society one of the first to be released and counting currently with 17 years of existence (IMBES[1]).

The enthusiasm of educators and policymakers to support their educational policies and practices with scientific evidence quickly caught the attention of the commercial companies to sell new learning techniques with science make-up (Goswami, 2006; Howard-Jones, 2014b). Teachers need to know how to disentangle whether what arrives at school comes from good scientific sources or pseudoscience, for less attentive or empowered teachers easily can be dragged along by speculative ideas, interfering with their pedagogical decision-making. Even with some notions of how we process information, it is not enough to understand how brain mechanisms work, and it may lead to erroneous theories about brain functioning (Thomas et al., 2019). Some assumptions can also be out of initial training and be more connected to popular contexts and everyday interpretations (Schregel and Broer, 2020). We knew that short-term training can impact personal beliefs and promote awareness about myths but do not develop full immunity to neuromyths (McMahon et al., 2019). People can have a profound interest in a topic and dive into non-scientific sources about it, and some popular courses about the brain can reinforce neuromyths (Hughes et al., 2020).

According to previous surveys, despite interest of teachers in brain topics, a high percentage believed in neuromyths. Moreover, this happens despite they are teachers from Portugal, Spain, England, The Netherlands, Turkey, or China (Dekker et al., 2012; Rato et al., 2013; Howard-Jones, 2014a; Ferrero et al., 2016). These studies illustrate how teachers will not always be explicitly aware of whether it is or not an evidence-based source. A recent systematic review focusing on the neuromyths popularity in educational contexts showed that brain misunderstanding is remarkably consistent among worldwide teachers and highlighted the need to improve the scientific content in higher education and the importance of in-service teacher training (Torrijos-Muelas et al., 2021).

[1] www.imbes.org

What contributes the most to these beliefs is not yet consensual, and data suggest that factors like age, education level, and neuroscience exposure influence neuromyths detection (Macdonald et al., 2017). Hence, it is not surprising that greater knowledge exchange in the context of teacher training already has been promoted by diverse international bodies (Coch, 2018). Examples of this are the Royal Society in the United Kingdom (2011), the International Society for Neuroscience (2009), and the Organization for Economic Co-operation and Development (2007), which all of them presented recommendations that preparation programs must include neuroscience components relevant to educational issues since we already have brain knowledge that should be central to the teacher and could provide to him another perspective on learning, development, and instruction (Leibbrand and Watson, 2010).

Knowing that for any professional domain, initial training plays a fundamental role in the success of the practice; we developed this study to verify which updated scientific knowledge coming from the neurosciences field can be accessed by teachers in their basic training. First, we analyzed the syllabus in the Portuguese reference courses for teacher education. And second, we surveyed the outreach books about the brain available in Portuguese and published in Portugal in recent years.

MATERIALS AND METHODS

Based on a double objective, we divided the study into the (1) Initial Teacher Training (ITT) syllabus survey and the (2) neuroscience outreach books rapid review.

Mind-Brain Curricular Units Present in the Teacher Training Courses

The Portuguese Elementary Education Degree (in Portuguese, *Licenciatura em Educação Básica*) is a 3-year course directed to prepare future professionals to deal with children from 0 to 12-year-old in school contexts. This ITT course is required to access the master's degree that enables later to teach pre-school and elementary years (Faria et al., 2016). It is the basic training for any future teacher and includes a total of 180 European Credit Transfer and Accumulation System (ECTS) credits. Through the DGES Database (Direção Geral do Ensino Superior[2]), we found the list of the higher school institutions and through their web pages (**Supplementary Appendix 1**); we scanned the public information. Thirty (N = 30) elementary education ongoing courses in the academic year 2020/2021 were reviewed to identify the curricular units related to the mind-brain scientific research domain. We used the following criteria for the analysis of the courses: name of the curricular unit, contents covered, unit objectives, and recommended bibliography. Unrelated curricular units, i.e., without mind-brain topics, were excluded from our selection process. Since the analysis was only based on publicly available information, the data limitations in several courses prevented us from relying on bibliographic criteria for robust conclusions. The main reason for selecting the courses for Early Childhood Education and Elementary Education is because

[2] https://www.dges.gov.pt/

these teachers will be the first line of contact between children and formal education, in which the importance of the early years in human development must be specially attended to in your training.

Books About the Brain Published in Portuguese

To review the books available with a brain subject focus, we used the National Library of Portugal online database (BPN—Biblioteca Nacional de Portugal[3]). The mission of the BPN is to gather, protect, and make available all knowledge in the Portuguese territory. With 200 years of existence, BNP acts as the National Bibliographic Agency and gathers its collection either through legal deposit or through the acquisition of works of a recognized bibliographic or cultural value, keeping a collection that exceeds 3 million publications (Biblioteca Nacional de Portugal, 2021). We defined a procedure similar to the systematic review for eligibility criteria, but as we were limited to a single database (i.e., BNP database is the only one with the national collection of this type of publications), we used a rapid review format for a quantitative approach (Grant and Booth, 2009). In records and titles in European Portuguese from 2015 to 2020, we collected the data with the terms including, brain, neuroscience, and neuropsychology using the advanced search option that allowed the use of Boolean operators (e.g., AND; OR). The database advanced option also allowed to limit the search to a specific catalog (i.e., science, educational, and outreach items), the years of publication, and personalize data output. The selection criteria for the book search were first based on the title (i.e., descriptors combination), then the summary, and index reading. The background of the authors was taken into account (if were from academia/clinician specialist in the field or not) acting as a myth-screening process. We excluded the academic thesis, non-dissemination books related to brain-mind themes (e.g., health legislation and national health reports), and books written in languages other than Portuguese. The terms selected simulate a basic search to learn about this main topic since it will also be the word brain or neuro-prefixes, the most searched for on the covers of books. The time frame of 6 years was defined to follow the same period of the revised initial teacher training courses and coincide with the latest government changes regarding curricula in Portuguese higher education. Three researchers were involved in the selection process, one screened each record, the other screened the list for a tiebreaker, and the third reviewed the final list obtained to check eligibility decisions.

RESULTS

Concerning the ITT courses, we found 30 open courses in Portugal among which, 20 are from public higher education and 10 from private institutions (**Table 1**). To understand the representativeness of the curricular units in the mind-brain domains, we analyzed the number of ECTS and the proportion considering the total of 180 ECTS for training completion. Based on the data that stand out, we figured out that the ISEC Lisboa is the higher institution that makes more investment in these domains presenting 10% of the required ECTS. The standard curricular unit in practically all courses is Developmental Psychology.

According to the list of applications for the first phase in 2020, the ITT courses only filled 71.3% (N = 630) of the open vacancies (N = 846). Despite our 20 public courses list, the official results of the entry grade average in higher education only count to 19. For reasons beyond our knowledge, the University of Évora does not appear. The grades (ranking between 0 and 20) of the last student admitted in the 19 public courses (M = 12.01; SD = 1.17) show the highest grade was 14.52 (Polytechnic Institute of Porto—Higher School of Education), and the lowest grade was 9.85 (Polytechnic Institute of Guarda—Higher School of Education, Communication, and Sports). Seven courses have filled all student vacancies, and four courses have less than five students each (DGES, 2020). In private institutions, this classifications entry system does not apply.

Of the 30 courses reviewed, we found 46 curricular units linked to human mind themes. No unit names were found with the prefix neuro (neither the term brain) or that explicitly addressed the link between neuroscience and cognition in the contents or objectives of the curricular unit (e.g., how the nervous system enables cognition). The selected units fall into the course general education category and were distributed across four major domains (**Table 2**). The available syllabus shows us that brain-based concepts are scarce, and the "mind-brain" domains only have a visible presence through classical theories about mental development (e.g., Piaget, Vygotsky). In the case of "Human Biology" and "Psycholinguistics," we only inserted the syllabus for the count whose we could verify that were within the mind-brain themes. While the psychology curricular units were more consensual about the topics approached, "human biology" without reference to the study of the nervous system and "linguistics" without the study of brain activity and structures were excluded from our final list.

As for the survey of books about the brain, applying our search descriptors, the BNP database showed us 272 records (**Figure 1**). Considering the exclusion criteria previously defined, we excluded a total of 132 records related to (i) academic thesis, (ii) duplicates (first edition only considered), (iii) non-scientific outreach books (e.g., health legislation and national health reports), and (iv) non-Portuguese written books.

We included 140 records from which we carried out a screening to classify the books to further fine the selection. As for the original language of the books, only 19% are written by Portuguese authors, in which the majority (81%) are translations from English, Spanish, and Italian. From our classification based on the BPN descriptions, we identified 78% outreach books, 8% textbooks, 6% exercises books for adults, and 8% for children/youth (i.e., brain-training exercise books). Within the outreach category, we looked into the books within the scope of the mind, brain, and education themes (N = 35).

The publication number shows an increasing trend over the last 6 years, with 2019 standing out compared with other years (**Figure 2**). In the distribution of percentages per year, 11% of publications were found in 2015, growing 1% in each of the following 2 years, reaching 19% in 2018 and 36% in 2019. In 2020,

[3]http://catalogo.bnportugal.gov.pt/

TABLE 1 | Initial Teacher Training (ITT) courses and European Credit Transfer and Accumulation System (ECTS) distribution by the curricular units with mind-brain subject domain (*N* = 30).

		Higher school institutions	ECTS by scientific domain: Developmental Psychology	Educational Psychology	Human Biology	Psycholinguistics	Total	%/180 ECTS	Access grade (M)
Public	1	University of Algarve	0	3	0	0	3	1.7	12.77
	2	University of the Azores–Faculty of Social and Human Sciences	3	0	6	0	9	5.0	11.76
	3	University of Aveiro	0	6	0	0	6	3.3	13.30
	4	University of Évora–School of Social Sciences	5	0	0	0	5	2.8	-
	5	University of Madeira–Faculty of Social Sciences	0	3	0	0	3	1.7	11.35
	6	University of Minho	5	0	5	0	10	5.6	13.26
	7	University of Trás-os-Montes e Alto Douro	0	0	0	0	0	0	12.18
	8	Polytechnic Institute of Beja–Higher School of Education	0	5	0	0	5	2.8	12.26
	9	Polytechnic Institute of Bragança	4	0	0	0	4	2.2	10.86
	10	Polytechnic Institute of Castelo Branco	3	3	0	0	6	3.3	11.27
	11	Polytechnic Institute of Coimbra	2	2	0	0	4	2.2	13.73
	12	Polytechnic Institute of Guarda	4	0	0	0	4	2.2	9.85
	13	Polytechnic Institute of Leiria–Higher School of Education	3	0	0	0	3	1.7	10.89
	14	Polytechnic Institute of Lisboa–Lisbon Education College	5	0	0	0	5	2.8	13.68
	15	Polytechnic Institute of Portalegre	4	0	0	0	4	2.2	-
	16	Polytechnic Institute of Porto–Higher School of Education	5	0	0	0	5	2.8	14.52
	17	Polytechnic Institute of Santarém–Higher School of Education	0	4	0	0	4	2.2	12.10
	18	Polytechnic Institute of Setúbal	4	0	0	0	4	2.2	11.28
	19	Polytechnic Institute of Viana do Castelo	5	0	0	0	5	2.8	11.16
	20	Polytechnic Institute of Viseu–Higher School of Education	4	0	0	0	4	2.2	11.23
Private	1	ISPA–University Institute of Psychological, Social and Life Sciences	6	0	0	0	6	3.3	-
	2	Higher School of Education of Fafe	6	0	0	0	6	3.3	-
	3	Jean Piaget Higher School of Education of Arcozelo	3	0	0	0	3	1.7	-
	4	João de Deus Higher school of Education	5	0	5	0	10	5.6	-
	5	Paula Frassinetti Higher School of Education	3	3	0	0	6	3.3	-
	6	Jean Piaget Higher School of Education of Almada	4	0	0	0	4	2.2	-
	7	Polytechnic Institute of Lusofonia–Higher School of Education	3	0	0	7	10	5.6	-
	8	Higher Institute of Educational Sciences	3	0	0	0	3	1.7	-
	9	Higher Institute of Educational Sciences of Douro	3	0	0	6	9	5.0	-
	10	ISEC Lisboa–Higher Institute of Education and Sciences	3	3	6	6	18	10.0	-
		Total	95	32	22	19	168		

TABLE 2 | Selected curricular units with mind-brain approach in the Initial Teacher Training (ITT) courses (*N* = 46).

Curricular Units	*Psychology of Development and Learnin g*	*Educational Psychology*	*Human Biology**	*Language Acquisition and Development**
	Developmental Psychology I and II	*Psychology of Education*	*Human Biology and Health*	Portuguese and Language Aquisition
	Childhood and Adolescence Psychology	Foundations of Educational Psychology	Human Biology and Health Promotion	Reading and Writing Psychogenesis*
	Child Psychology		Human Body and Health	Language, Cognition, and Plurilingual*
Main scientific domain	Developmental psychology (*n* = 26)	Educational psychology (*n* = 9)	Human biology (*n* = 5)	Psycholinguistics (*n* = 6)

**Optional unit; in italics more than one record.*

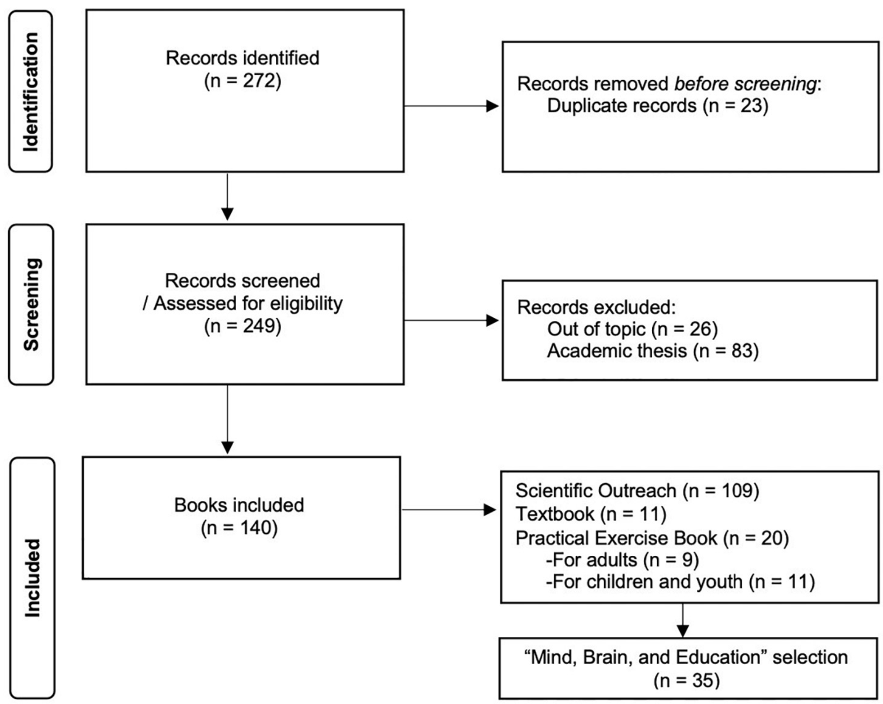

FIGURE 1 | Flow diagram of the brain topic publications via the database of the National Library of Portugal.

it drops to 9%, and we verified that this break in the growing trend is probably due to the mandatory stop of the publishers caused by the COVID-19 pandemic. However, the 2019 difference also could be related to the Neuroscience and Psychology collection, where only this year, 16 books were distributed by a Portuguese weekly magazine of general information. Between 2015 and 2020, we found that the books *Open brain!* (2015), *The child's brain explained to parents* (2016), and *The brain: a story of you* (2017) were the top three books reprinted in Portugal, assuming a higher sales volume.

Within the included books list (*N* = 140), we selected those that presented valuable content for teachers to learn about the neuroscience of learning, reading, identity, language, memory, and attention (*N* = 35). **Table 3** presents our mind, brain, and education selection books describing a brief content analysis of these publications. Most of the 35 selected books (Damásio, 2015; Searle, 2015; Bilbao, 2016; Castro Caldas, 2016; Cotrufo, 2016, 2019; Dierssen, 2016, 2019; Sena, 2016; Fonseca, 2017; Rato and Castro Caldas, 2017; Rego et al., 2017; Lauffer, 2018; Matute, 2018; Sigman, 2018; Alonso, 2019; Berardi, 2019; Bote, 2019; Burgaya-Márquez, 2019; Canessa, 2019; Caruana, 2019; Daphna, 2019; Domínguez, 2019; Garcia, 2019; Maojo, 2019; Quintero and Álamo, 2019; Sepulcre, 2019; Tafet, 2019; Viosca, 2019; Castro Caldas and Rato, 2020; Correia and Ferreira, 2020) are written by academics or clinicians in the fields of medicine, neuroscience, and psychology, with four exceptions to report (10, 11, 13, 15, refs number in **Table 3**). The guide for discovering the brain by Martins et al. (2017), was written by the writers of children books; however, the contents were reviewed by a panel of scientific experts. The book about how students can get better grades (Gaspar, 2018) is authored by a math teacher responsible for the Neurosup project to help French students and

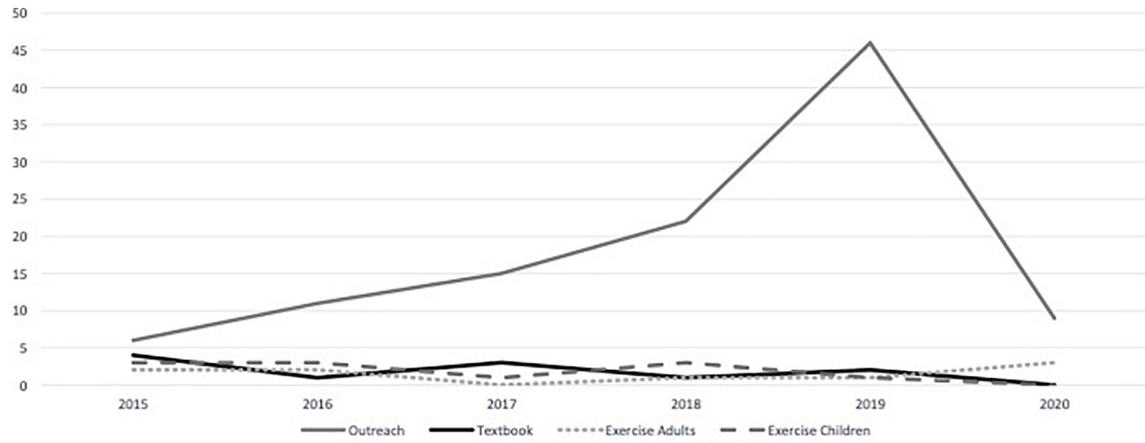

FIGURE 2 | Brain-related books published (2015–2020).

teachers learn better using neurosciences, although no scientific evidence on the impact of the project was found so far. Two books (10, 15) were written by non-scientific background writers (Gifford, 2017; Ibánez, 2018) with experience in outreach for a broader public.

Of the 35 books in review, we selected those that explicitly bridged the gap between neuroscience and education by addressing, in simple language, important themes, such as brain plasticity, types of memory, and the brain of teenagers, demystified some erroneous concepts, or explored the potential of interdisciplinary knowledge of applications in the classroom (marked in bold in **Table 3**). Of these 35, we highlighted 18 books, written or reviewed by experts, that fulfill the outreach function by disseminating in a useful and clear way, brain content to the educational community. Topics, such as the construction of memories and the relationship between emotions and learning, are the most frequently discussed in these publications and we also found two books that explicitly aim to debunk neuromyths (11 and 34 in **Table 3**).

DISCUSSION

Concerns about the academic skills of prospective teacher candidates are recurrently featured in education quality policy discussions around the world (OECD, 2019). Portugal is not an exception, and with this study, we aimed to take a picture of the state of curriculum programs in terms of the presence of up-to-date content about the learning brain. Results showed that teaching training includes scientific domains related to the psychology of education and development, being these the most representative of the mind-brain domains searched. However, we did not directly connect with neuroscientific knowledge since the syllabus analyzed does not evidence this domain, either in the content or in the recommended bibliographical references. Curricular units linked to human biology and psycholinguistics were also identified, but far from representative, given the sparse number of units with the majority being proposed as optional.

Despite the psychology domain content presence, brain knowledge has been deeply absent from the Portuguese teacher's initial training. With few recent bibliography lists, the historical foundations of psychology and the classic models of child development (e.g., Piaget and Vygotsky theories) are the topics mostly present in the psychology disciplines examined. Also, the revised syllabus does not address the mind, brain, and education integrated view, not even in a slight way. This is in line with the National Council on Teacher Quality report, which indicates that most of the teacher education courses and textbooks in the United States do not cover principles from cognitive psychology related to evidence-based learning, and some of them propagate learning misunderstandings (Pomerance et al., 2016).

Trying to implement popularized strategies, such as the multiple intelligences, the learning styles, or the brain gym, may not be the best use of teacher's time and, as Weinstein and Sumeracki (2019), we also believed that teachers and researchers can benefit from an open dialogue about the learning science research evidence. It is not new the suggestion that curricular subjects, such as psychology, neuropsychology, and neuroscience in a course syllabus, are one possible way to narrow the knowledge gap concerning how the mind works (Damasio, 2008). According to Liebowitz et al. (2018), the coursework should efficiently introduce key theory embedded into learning sciences, while primarily supporting teaching candidates in building skills in response to the realities they face in their classrooms. However, by our results, Portuguese teachers may be still far from this achievement, especially concerning updating neuroscientific knowledge applied to education.

Providing new tools drawn from scientific research does not have to go through the prescription way (Brookman-Byrne and Thomas, 2018). Involving teachers at the early stages of research projects, shaped by their needs, could help them choose the most appropriate method for a given scenario in their classroom. The Portuguese teacher's profile recommends that in

TABLE 3 | Outreach books selection with mind, brain, and education themes (*N* = 35).

Year		Author(s)	Books title in English (title in the Portuguese edition)	Content
2015	1	Searle, John R.	Mind, brain and science (Mente, cérebro e ciência)	A philosophy approach about mind, body, and consciousness as a function of the brain. Intending to connect common sense knowledge and scientific research data and reflection it also introduces the reader to the main problems of the philosophy of the mind.
	2	Damásio, António	Descarte's error (O erro de Descartes: emoção, razão e cérebro humano)	A 1995 bestseller that is re-released in an updated version. It is an invitation to a journey of discovery of the connection between emotion and reason. also serves as an introduction to modern cognitive neuroscience.
2016	**3**	Castro Caldas, Alexandre	Life of the brain (A vida do cérebro: da gestação à idade avançada)	An invitation to learn about the brain from its formation in the embryo, through the first months of the baby's life, then entering the period of adolescence, passing through adulthood, and ending at a more advanced age.
	4	Sena, Armando	Brain, health and society (Cérebro, Saúde e sociedade)	An introductory textbook about the brain with perception and memory descriptive chapters.
	5#	Dierssen, Mara	The artistic brain: creativity and neuroscience (O cérebro artístico: a criatividade segundo a neurociência)	With the resources humans used in Arts, what is the biological meaning of it? Years and years of the creation of beautiful pieces of art as a means of expression. Our species created patterns of shapes, light, colors, and symbols. This book is an introduction to the analysis of neuroscience on human art.
	6#	Cotrufo, Tiziana	The brain and the emotions (O cérebro e as emoções: sentir, pensar, decidir)	Outreach book about the biological functioning of emotions.
	7	Bilbao, Álvaro	The child's brain explained to parents (O cérebro da criança explicado aos pais)	Presented as a practical manual that summarizes the knowledge that neuroscience could provide to parents and educators to help children achieve full intellectual and emotional development.
2017	8	Fonseca, Vítor	Neuropsicomotricity: essays about the relationship between body-motricity-brain-mind (Neuropsicomotricidade: ensaio sobre as relações corpo-motricidade-cérebro-mente)	The study of the connections between body, brain, mind, and motricity has improved with the research in neuroscience and neuroimaging. Research on these topics goes deep since the beginning of our species evolution. This book is a narrative perspective of our development as a species focusing on the action that shaped our mind and brain.
2017	9	Rego, Ana Cristina; Duarte, Carlos; Oliveira, Catarina	Neurosciences (Neurociências)	Neuroscience textbook is written for college students. It addresses topics, such as the central and peripheral nervous system, neurotransmission processes, the cellular, and molecular bases that determine the formation of memory, the dysfunctional and pathological processes associated with stress, and neuropsychiatric diseases, among other topics that underlie a basic neuroscience curricular unit.
	10	Gifford, Clive	The Human brain in 30 seconds (O cérebro em 30 segundos)	Each topic is presented in a neat 30-s soundbite, supported by a 3-s flash summary and full-page, colorful illustration. Active "missions" support the topics and encourage children to find out more. The attention-grabbing format is engaging and immediate, introducing readers aged from eight up to this part of their bodies called the brain.
	11	Martins, Isabel Minhós Pedrosa, Maria M.	Inside. Guide for discovering the brain (Cá Dentro. Guia para descobrir o cérebro)	Designed to satisfy the curiosities about the working of the mind and brain. It's an illustrated book, written and designed with the collaboration of a team of psychologists and researchers. This is a book aimed at children and youth.
	12	Rato, Joana; Castro Caldas, Alexandre	When your son's brain goes to school (Quando o cérebro do seu filho vai à Escola: boas práticas para melhorar a aprendizagem)	There's a growing desire to apply neuroscience in education, but science moves at a different speed than expectations. In this science outreach work, the authors promote the research conducted scientifically and highlight the study of the learning brain.

(Continued)

TABLE 3 | (Continued)

Year		Author(s)	Books title in English (title in the Portuguese edition)	Content
2018	13	Gaspar, Éric	How do get better grades at school? (Como ter as melhores notas da escola: o cérebro e os seus truques: é fácil conseguires!)	How to memorize better to get better grades at school? This book is a fun guide to improve school grades, with strategies based on neuroscience research and tips to study better.
	14#	Matute, Helena	The mind trick us: bias and errors we made (A mente engana-nos: desvios e erros cognitivos que todos cometemos)	With the starting point of "we don't think without errors", this book analyses the bias and distortions of the human mind. Examples from daily life are analyzed by research in psychology.
	15	Ibánez, Álvaro Ferández	The SharpBrains guide to brain fitness: how to optimize brain health and performance at any age (Como investir no seu cérebro?)	This edition combines a user-friendly tutorial on how the brain works with advice on how to choose and integrate lifestyle changes and research-based brain training. Featuring an analysis of hundreds of scientific studies published in the last 10 years, the book also includes in-depth interviews with 20 leading scientists about brain health thinking and care.
	16	Sigman, Mariano	The secret life of the mind: how your brain thinks, feels, and decides (A vida secreta da mente: o nosso cérebro quando decidimos, sentimos e pensamos)	Draws on research in physics, linguistics, psychology, education, and beyond to explain why people who speak more than one language are less prone to dementia; how infants can recognize by sight objects they've previously only touched; how babies have an innate sense of right and wrong, even before words; and how we can "read" the thoughts of vegetative patients by decoding patterns in their brain activity.
2019	17#	Caruana, Fausto	The empathic brain (O cérebro empático: como funciona a compreensão do outro?)	Philosophy established the concept of empathy at the beginning of the twentieth century. How the idea evolved to our days? This book review different models that look at empathy and uncover the biological mechanisms that underlie this process.
	18#	Bote, Rubén Moreno	How we make decisions (Como tomamos decisões: os mecanismos neuronais da escolha)	Even the most minor decision uses different neural paths and complex operations in the biology of decision making. This book collects scientific evidence about decision-making and is a contributor to a more profound understanding of some errors we made.
	19#	Domínguez, Daniel Gómez	Math and neuroscience (Matemática e neurociência)	From the ability to count and our numeric system to specific algorithms, we have a mystery: how do we deal with this complexity? This book aims to study the neurologic basis of our number sense and the connection to math.
	20#	Garcia, Emílio García	We are our memory (Somos a nossa memória)	Explores the complexity of the memory systems and how they affect our human life.
	21#	Viosca, José	Extraordinary minds (Mentes prodigiosas: fundamentos psicológicos e neuronais das capacidades excecionais)	What happened in the brains of Einstein, Mozart, or Curie? There are persons with an extraordinary capability in a specific filed, how they mind worked? What are the limits of the human mind? This book tries to answer these questions with reflections about scientific research.
	22#	Quintero del Álamo, Javier	The teenage brain (O cérebro adolescente: uma mente em construção)	This book explores neuroscientific research about the adolescent brain and transformations during puberty. It aims to inform the reader about behavior typical in this age and neurological changes.

(Continued)

TABLE 3 | (Continued)

Year		Author(s)	Books title in English (title in the Portuguese edition)	Content
	23#	Lauffer, Javier Correas	Pleasure and reward (Prazer e recompensa: os mecanismos da motivação)	This book is about the role of dopamine in the nervous system and its connection to human behavior. It also analyzes everyday habits like using social networks (like Instagram or Facebook) in the light of neuroscientific research.
	24#	Burgaya-Márquez, Ferran	Does the brain have a sex? Desire, gender, and sexual identity (O cérebro tem sexo? Desejo, género e identidade sexual)	This book is about how our brains work (learning mechanisms, memory) and contribute to human sexuality. This research also connects this data with the concepts of sex and gender.
	25#	Sepulcre, Jorge	Neural networks and functional plasticity (Redes cerebrais e plasticidade funcional: o cérebro que se modifica e se adapta)	The structure of the brain, connectivity, and network theory.
	26#	Dierssen, Mara	How the brain learns and remembers? [Como aprende (e recorda) o cérebro? Princípios de neurociência para aplicar à educação]	An introduction to neurobiology learning for the general public.
	27#	Maojo, Víctor	Brain and music (Cérebro e música: entre a neurociência, a tecnologia e a arte)	How the brain reacts to music and how it interprets.
	28#	Canessa, Nicola	Reason's dream: how the brain works [O sonho da razão: como funciona o cérebro]	Introduction to neuroscience for a new audience. New translation with scientific revision.
	29#	Cotrufo, Tiziana	In the child's mind [Na mente da criança: o cérebro nos primeiros anos]	It presents data from research about the development of the human brain in the first years of life. There is a particular highlight to the research about "critical periods" in learning competencies as language and math and the development of memory.
	30#	Tafet, Gustavo E.	Stress: what it is and how it affects us? (Stress: o que é e como nos afeta)	An exploratory text about understanding stress at a psychological and neurological level. New translation with scientific revision.
	31#	Alonso, Tomás Ortiz	Neuroscience at home: more than homework (Neurociência em casa: mais do que os trabalhos escolares)	To fill in the gap between neuroscience and education, connect research about learning processes related to school and highlight main evidence.
	32#	Berardi, Nicoletta	Environment, plasticity, and brain development (Ambiente, plasticidade e desenvolvimento cerebral)	A book about the role of the environment in neural development.
	33	Daphna, Joe	Gender mosaic (Cérebro e género)	It addresses a controversial topic theme linked to sex differences in the brain explains why there is no such thing as a male or female brain and no neural basis for differentiating people based on sex.
2020	**34**	Castro Caldas, Alexandre; Rato, Joana	Neuromyths (Neuromitos. Ou o que realmente sabemos sobre como funciona o nosso cérebro)	Myths about the mind and the brain are spread across the world. The authors explore each neuromyth and debunk them with evidence gathered in scientific research.
	35	Correia, Patrícia; Fonseca, Ana Rita.	The book of the brain: find out what's inside of your head (O livro do cérebro: descobre o que vai na tua cabeça)	Containing several illustrations and schematic information about the brain anatomy and function was developed for children, but present useful content for all ages.

#Belongs to a book collection. Bold contributes to bridging neuroscience to education.

their professional activity teachers should participate in research projects related to teaching, learning, and student development (DRE, 2001), but analyzing the contents that are worked on in initial training, it seems difficult for these teachers to feel prepared to execute projects on the subject of mind, brain, and education.

Previous studies revealed that Portuguese teachers are very interested in training in these domains and the lack of scientific literacy can contribute to their easily succumbing to neuromyths (Rato et al., 2011, 2013). If on the one hand, we have teachers fascinated to learn more about how the brain works, on the other hand, teacher training itself is losing demand. Our data review of the ITT courses suggests a growing lack of interest to follow a teaching career since these courses are getting low-grade students and have lost candidates over time. Adding to this scenario, we noted that only 2% of Portuguese students express a desire to be a teacher in the PISA report (5% on the OECD average), which are also the ones with low rankings in literacy and mathematics (OECD, 2015). These are enough reasons to make us conclude that the social devaluation of the teaching profession in Portugal is currently a reality.

If the interest in the educational vocation were equal to the general fascination with neuroeducation topics, we would no longer have a problem to solve. Our results show an increase in the number of publications about brain discoveries in the last 6 years. As for the book category, there were more outreach books found, although brain stimulation exercise books were higher produced, compared with textbooks. We also noticed that the available books in European Portuguese are mostly translations, with few Portuguese academics specialized in writing books for the general public. Furthermore, not all of the brain outreach books reviewed are written by experts in the neuroscience field, which also makes this kind of publication more vulnerable to speculation (i.e., the spread of pseudoscience/myths). Nevertheless, the publications reviewed that have school teachers as a target, and which main subjects are addressed to bridge the interdisciplinary area of the mind, brain, and education, remain scarce. As such, it is not run out yet the production of these materials for the educational audience with a scientific quality label. We also realized that even Portuguese researchers with an expressive scientific contribution in the field of relationship between brain sciences and education may not have science extension materials recently published (e.g., Morais, 1997) or authors who may not have the proper recognition in Portugal since their books remain untranslated into Portuguese so far (e.g., Tokuhama-Espinosa, 2018; Dehaene, 2020).

We knew that neuroscience has a major presence in psychology than in education research (Bruer, 2016), and we also knew that the psychology literature has been playing a fundamental role to inform educational settings (Mason, 2009). But, none of this seems enough to reach an interdisciplinary knowledge dialogue, which is structural to the educational success of neuroscience as a field. The brain research contribution, jointly with extensive dissemination and translational work, is increasingly needed to an integrated learning research enterprise for school best practices.

Limitations and Future Work

As limitations, we highlighted the restraint on public data that when not available unallowed to draw strong conclusions regarding the recommended bibliography in the reviewed courses. However, we also recognized that there may be a wide variability since the same content can be approached differently depending on the training or updating of teachers, which may be a good indicator to explore in future studies. Another weakness is due to the library database used since it is not prepared for the application of typical procedures on a scientific basis (e.g., refined filters and data export), making advanced surveys less accurate and reliant on manual final verification. Also, due to not achieving a full reading and a fact-check, the scientific quality of the reviewed books was based on the broad subjects and authorship expertise, so further studies are required to thoroughly analyze the neuro-prefix materials and workshops or other events that enter schools. A review of the publications to the general public by panel-of-expert would help to distinguish what is pseudoscience from the issues covered in a scientifically supported way.

CONCLUSION

The main contribution of the study was to present an exhaustive curricula picture in future training of teachers on Early Childhood Education and Elementary Education and the brain-mind outreach books published in Portugal. The recent explosion of mass-produced information about brain discoveries runs counter to what we see embodied in teaching curricula. Improving the units within the general education category in the ITT courses with an integrated mind-brain-education updated program appears urgent and a possible path to stop misinformation and the spread of educational practices so-called based on the brain but without scientific evidence. Achieving EBPs in schools also involves preparing the educational professionals for scientific literacy right from the beginning of their training. The teacher preparation programs should be seen as a good investment and here neuroscience can play a modest, but booster role in building an evidence-based learning education culture. Still few reference researchers who work on the relationship between brain sciences and education published outreach books for Portuguese educational communities. Quality science communication publications can narrow the scientific brain knowledge gap in educational professionals but, in this case, is dependent on their interest and careful interpretation of this kind of literature.

DATA AVAILABILITY STATEMENT

The original contributions presented in the study are included in the article/**Supplementary Material**, further inquiries can be directed to the corresponding authors.

ETHICS STATEMENT

Research protocol was approved by the Comissão de Ética para a Saúde (CES)—Universidade Católica Portuguesa (ref. number 131/2021). Written informed consent was not required in this study in accordance with the national legislation and the institutional requirements.

AUTHOR CONTRIBUTIONS

JR and AC-C outlined the research idea. JA collected and processed the data. All authors contributed to the writing and reviewing of the manuscript.

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SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fpsyg.2022.737136/full#supplementary-material

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What Does the General Public Know (or Not) About Neuroscience? Effects of Age, Region and Profession in Brazil

Analía Arévalo[1†], Estefania Simoes[2†], Fernanda Petinati[3] and Guilherme Lepski[1,4]*

[1] Division of Functional Neurosurgery, Department of Psychiatry, Medical School, University of São Paulo, São Paulo, Brazil, [2] Cancer Metabolism Research Group, Cell and Developmental Biology, University of São Paulo, São Paulo, Brazil, [3] Psychotherapy Department, Institute of Psychiatry, University of São Paulo, São Paulo, Brazil, [4] Department of Neurosurgery, Eberhard Karls University of Tübingen, Tübingen, Germany

Edited by:
Arun Bokde,
Trinity College Dublin, Ireland

Reviewed by:
Jovana Bjekic,
University of Belgrade, Serbia
Lang Chen,
Santa Clara University, United States

***Correspondence:**
Analía Arévalo
analia.l.arevalo@gmail.com

†These authors have contributed equally to this work

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The field of Neuroscience has experienced a growing interest in recent decades, which has led to an exponential growth in the amount of related information made available online as well as the market for Neuroscience-related courses. While this type of knowledge can be greatly beneficial to people working in science, health and education, it can also benefit individuals in other areas. For example, neuroscience knowledge can help people from all fields better understand and critique information about new discoveries or products, and even make better education- and health-related decisions. Online platforms are fertile ground for the creation and spread of fake information, including misrepresentations of scientific knowledge or new discoveries (e.g., neuromyths). These types of false information, once spread, can be difficult to tear down and may have widespread negative effects. For example, even scientists are less likely to access retractions of peer-reviewed articles than the original discredited articles. In this study we surveyed general knowledge about neuroscience and the brain among volunteers in Brazil, Latin America's largest country. We were interested in evaluating the prevalence of neuromyths in this region, and test whether knowledge/neuromyth endorsement differs by age, region, and/or profession. To that end, we created a 30-item survey that was anonymously answered online by 1128 individuals. While younger people (20–29-year-olds) generally responded more accurately than people 60 and older, people in the North responded significantly worse than those in the South and Southeast. Most interestingly, people in the biological sciences consistently responded best, but people in the health sciences responded no better than people in the exact sciences or humanities. Furthermore, years of schooling did not correlate with performance, suggesting that quantity may surpass quality when it comes to extension or graduate-level course offerings. We discuss how our findings can help guide efforts toward improving access to quality information and training in the region.

Keywords: neuromyths, neuroscience, public knowledge, education, higher learning

INTRODUCTION

The field of neuroscience has significantly grown worldwide in the last few decades. Interestingly, since the 1990s (known in the United States as the Decade of the Brain), interest in and the pursuit of knowledge in this field have only seemed to grow (OECD, 2002; Dekker et al., 2012). According to PubMed, in the mid 1960's, an average of 3,000 articles including the word "brain" were published per year; in 2019, this number increased to 94,615 (Markram, 2013; Fan and Markram, 2019; Tokuhama-Espinosa, 2019).

Neuroscience-related topics represent critical general knowledge and information in modern society and are therefore relevant for a wide range of professions and lifestyles. Among other things, neuroscientific knowledge can help one learn faster, read better, acquire motor or sports-related abilities, improve quality of sleep, increase concentration, and stabilize one's emotions (Landi et al., 2013; Stanley and Krakauer, 2013; Dubinsky et al., 2019; Humeau et al., 2019; Klinzing et al., 2019; van Kesteren and Meeter, 2020). It can also help educators improve their teaching strategies and learners improve their performance, which can in turn orient important educational and health policies (OECD, 2002; Goswami, 2006; Howard-Jones, 2014; Dubinsky et al., 2019). Critically, neuroscience-related knowledge can help prevent discrimination in society, by eliminating old inaccurate views regarding biological differences among genders, races, or cultural or socioeconomic groups.

Among the first 50 result pages of a simple Google search conducted in July of 2020, we found more than 400 free/open courses in Neuroscience or Neuroeducation offered in Brazil. This high number of free courses suggests a growing interest among Brazilians in pursuing academic training in Neuroscience-related areas. Almost all the courses we found are offered online for free or at an affordable cost. Furthermore, the average number of hours required for course completion is a mere 24 (maximum 80), which may arguably not be enough time to gain expertise (but see Darling-Hammond et al., 2011). Most interestingly, less than 10% of these courses were associated with an accredited higher learning institution, making it difficult to determine the quality of the content offered. Among longer graduate-level extension courses, only 11 (less than 3%) are offered by universities that are well placed in the Ministry of Education's (MEC) most recent general course index (IGC, 2018). Reduced cost and time investment may be attractive features when choosing a course, particularly when consumers have little access to reliable reviews or evaluations of the countless products available. In sum, there is a great supply of courses for an increasing demand, but it is difficult to assess the quality or effectiveness of these courses.

While scientists in any part of the world are trained to analyze and critique information (scientific or otherwise), through people rely mostly on big media or online venues for access to new research, theories and discoveries. But what kinds of scientific information can laypeople access though these sources? In Brazil, several companies and portals translate scientific research to lay language, but this is often done by non-specialized journalists. Currently, there are more than 31,306 communication companies in Brazil (Grupo de Mídia São Paulo, 2019), and approximately 16,477 online portals (We are Social, 2020).

While in other countries such as the United States, people have also reported using the internet as their main source of information (Zambo and Zambo, 2009), these numbers are even higher in Brazil. Globally, 59% of people have access to the internet, and 49% of those people use at least one social media platform. In Brazil, these numbers are 66% and 71%, respectively. Also, while average internet use per day worldwide is 6 h and 42 min, average daily use in Brazil is 9 h and 29 min, with 85% of Brazilians going online on a daily basis (We are Social, 2020).

The recent phenomenon of Fake News has largely contributed to the public's general misinformation regarding healthcare knowledge (Merchant and Asch, 2018), which could have long-lasting negative effects, especially when such misinformation infiltrates areas such as basic education. Misinformation can lead to misguided educational methods that could affect generations to come (Peters, 2018) and negatively impact decision-making, driving entire communities toward choices that are not scientifically sound (Scheufele and Krause, 2019), such as anti-vaccination movements (Chiou and Tucker, 2018) or the endorsement of inappropriate medical treatments (Lavorgna et al., 2018). In 2018, Brazil's Ministry of Health launched a secure WhatsApp line to answer people's questions regarding online information; the report they provided at the end of one year revealed that 77% of questions answered were based on fake news[1].

Brazil is a country of continental proportions, in terms of size and in the number of different cultures, socioeconomic levels and methods of information consumption (IBGE, 2021). In order to take on the challenge of improving the quality of available information and training (both inside and outside academic settings), one must understand where the biggest problems lie. To this end, we used the most searched neuroscience-related terms and questions to create a survey of 30 true/false statements which we distributed among our personal and professional contacts all over Brazil and published on several social media platforms. We obtained anonymous responses from 1128 individuals representing different age groups, regions within Brazil and professions.

Our motivation for assessing whether profession made a difference in performance was to see whether assumptions about knowledge among people in different fields were upheld (e.g., people in health or science should know more about neuroscience than people in the humanities or the exact sciences). Similarly, we wanted to investigate whether people in different regions performed differently because regions in Brazil are unequally favored in terms of wealth, resources and education: total years of schooling are significantly higher and illiteracy rates are significantly lower in the South and Southeast relative to the North and Northeast (IBGE, 2021). A study conducted by the Brazilian Institute for Geography and Statistics (Instituto Brasileiro de Geografia e Estatística, IBGE) in 2018 revealed that internet use is highest among 18–29-year-olds (90–91%), and

[1] https://www.saude.gov.br/fakenews

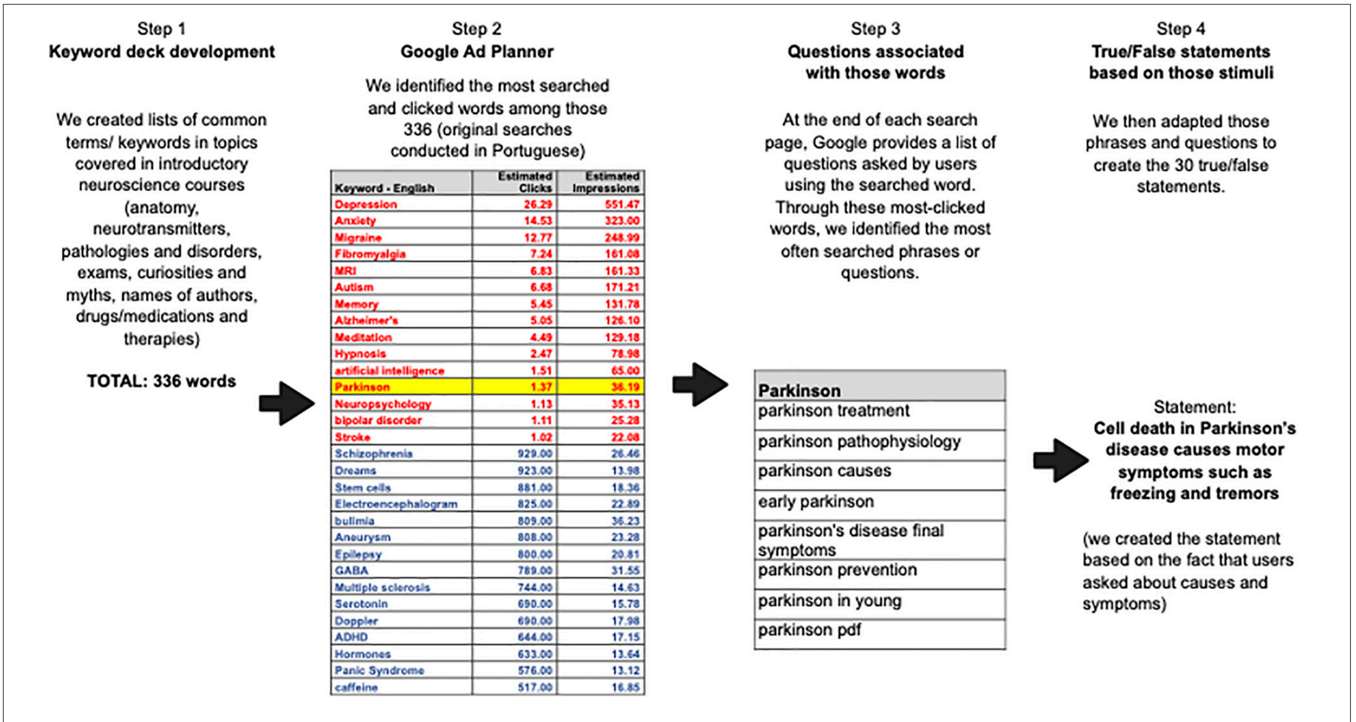

FIGURE 1 | Flowchart showing the steps taken to create the survey.

lowest among individuals 60 and older (38.7%), with steadily declining numbers as age increases (IBGE, 2018). Thus, given that much information (accurate or inaccurate) is obtained from the internet (Markram, 2013), and internet use is not equal across age groups, we questioned whether performance would also vary among the age groups tested.

In terms of specific answers, we expected better performance on statements regarding vaccines and disorders (e.g., Alzheimer's Disease, Parkinson's Disease, autism and epilepsy), as these are often covered in the media. We also expected relatively good performance on statements about child development, which is also widely publicized and discussed (on YouTube channels, blogs and social media platforms). In contrast, we expected lower performance on common neuromyths (e.g., brain size and intelligence, differences between female and male brains), see **Figure 1** for a graphic illustration of this 4-step process as these are often perpetuated in films and TV (among other sources), and on more complex topics requiring a deeper understanding of neuroscience (e.g., neuronal function, systems neuroscience), as these concepts are more complex and are usually covered in formal courses.

Our goal was to obtain a clearer picture of general knowledge across these groups, including specific knowledge gaps, as well as which neuromyths are endorsed the most. In the short term, this information can help guide new and better ways of improving scientific communication. In the long term, this information could motivate the development of better-quality courses (e.g., undergraduate, graduate, extension, and free). For survey participants who expressed interest, we made available a document containing the answers and explanations for each statement written in simple lay terms, as a small initial contribution to the spread of science-based information (see **Supplementary Figure 1**).

MATERIALS AND METHODS

Procedure

In a pilot study conducted by our group in 2018, 401 participants anonymously responded to a Google survey containing questions and statements about general knowledge in neuroscience, which we created based on previous publications in the field and on conversations with colleagues and students. All four authors of this article are closely involved with a multi-professional extension course in neuroscience offered at University of São Paulo's Medical School (two are the course's coordinators and two are ex-students); some of the questions were created based on students' questions asked at the beginning of that course. Those pilot data were not published because we noticed a number of flaws with the way some questions were presented (e.g., unclear wording), but it did help us identify valid questions and contributed to the creation of the subsequent survey (see below). For example, in one open answer question, participants were asked what they would ask a neuroscientist if they were to meet one at a party. The answers to that question provided us with important insight into individuals' doubts and curiosities.

Then, in 2019, we took on the challenge one more time. However, this time, we used a different approach.

Step 1: Each of the authors created lists of common terms or keywords in the following areas commonly covered in introductory neuroscience courses: anatomy, neurotransmitters, pathologies and disorders, exams, curiosities and myths, drugs/medications and therapies. This yielded a total of 336 words (see **Supplementary Table 1**).

Step 2: We then inserted those words into the Keyword Planner within Google Ads (Google's tool for creating advertisements on Google's platform and networks) and identified the number of searches and clicks for those words in Brazil for an entire year (between early 2018 and April 2019). This allowed us to identify the 15 keywords with the largest click volume in Brazil within that period.

Step 3: Next, we conducted simple Google searches using those 15 words (and an additional 15 words chosen from the pilot study described above) to identify the questions most often associated with those keywords within searches. In other words, through these most-clicked words, we were able to identify the most often searched phrases or questions (see **Supplementary Table 2**), which we then used to create the 30 true/false statements. Basically, our stimuli were adaptations of the questions we identified (Step 4).

The survey was administered via Google Surveys and was made available on the authors' and colleagues' social media platforms between September 9th and October 16th, 2019. It was also distributed to colleagues, students, friends and family in all five regions of Brazil, who in turn shared with their own personal and professional networks.

Order of presentation was balanced to avoid clusters of true or false answers or similar themes and all participants viewed all 30 statements in the same order. Only after answering each question could participants view and answer the following question. **Table 1** lists all 30 statements, overall response accuracy for each, and whether answers varied by age, region or profession.

The study was carried out in accordance with the Declaration of Helsinki. While ethical compliance varies across countries and institutions, online questionnaires to unidentified adults generally do not require IRB approval, which was the case at our institutions. In line with the *Ethical Standards of the American Educational Research Association* (Strike et al., 2002), the recommendations for good practice in designing internet-based research (Gupta, 2017), and *Mixed Methods Research Methodologies* (Terrell, 2012), or our online survey, we were transparent in recruiting, considered participant privacy and ensured secure communication protocols, obtained informed consent, allowed participants the opportunity to withdraw from the research at any time, and did not subsequently use the data for unethical practices. We also explained the study's purpose, indicated that anonymity would be protected at all times by never collecting (or storing) name or any other identifying information, and coding answers so that these could not be associated with a particular participant. The first page of the survey explained these issues and asked participants whether they agreed with their anonymous answers being used in the research study. Answers from those who did not agree were excluded from the database before analyses were conducted.

TABLE 1 | Number of participants in each region and percent of total.

Region	Number of participants	% of total
North	44	3.90
Northeast	154	13.65
Midwest	41	3.63
Southeast	756	67.02
South	109	9.66
Not declared	24	2.13
TOTAL	1128	100

TABLE 2 | Number of participants in each age group and percent of total.

AGE groups (in years)	Number of participants	% of total
10–19	41	3.63
20–29	266	23.58
30–39	380	33.69
40–49	236	20.92
50–59	137	12.15
60 and older	68	6.03
TOTAL	1128	100

Participants

A total of 1128 individuals provided online anonymous answers to the entire survey and provided information regarding age (10–60+), profession (biological sciences, exact sciences, humanities, health sciences, retired, not working, or other) and region (South, Southeast, Midwest, North, or Northeast). These questions were presented in a multiple-choice format. Also, in a free answer format, they were asked to indicate their last (completed or incomplete) level of schooling (from grammar school to post-doctoral work), the number of years in their declared profession, and total number of years of education (as this can vary in Brazil even within the same degree). All surveys that were completed in their entirety and submitted (n = 1128) and for which participants gave consent, were included in the analyses.

In terms of age, 34% (n = 380) of participants were in the 30–39 group, 24% (n = 266) were in the 20–29 group, 21% (n = 236) were in the 40–49 group, 12% (n = 137) were in the 50–59 group, 6% were in the oldest group (60 or older; n = 68), and 4% were in the youngest group (10–19 years old; n = 41) (**Table 2**).

In terms of Brazilian regions, most participants were from the Southeast (n = 756; 67%), followed by the Northeast (n = 154; 14%), South (n = 109; 10%), North (n = 44; 4%) and Midwest (n = 41; 4%). Twenty-four participants (2%) did not declare region and were thus excluded from analyses based on this variable (**Table 1**).

In terms of profession, 36% (n = 405) of respondents declared studying or working in the humanities, 27% (n = 307) in the health sciences, 9% (n = 104) in the exact sciences, 8% (n = 92) in biological sciences, and 20% (n = 220) declared other, retired, or not working (**Table 3**).

While we had no way of controlling the number of participants that would respond from each region as responses were entirely voluntary (and we used a snowball sampling method), the number of respondents from each region was strikingly

TABLE 3 | Number of participants in each profession and percent of total.

Profession	Number of participants	% of total
Biological sciences	92	8.16
Exact sciences	104	9.22
Humanities	405	35.90
Health sciences	307	27.22
Other/Retired/Not working	220	19.50
TOTAL	1128	100

proportional to national regional populations. **Table 4** below shows population by region in Brazil and in the current study, as well as the percentage each sample represents of the larger population. A chi-squared test revealed that the regional distributions did not differ significantly between our study and the total population (all chi-square *p*s > 0.05; see **Table 4** for chi-square values).

Survey

The 30 statements that made up the survey were viewed and responded by all participants in the same order (see **Table 5**).

RESULTS

Score Distribution

We first tested and confirmed the normality of the score distribution (Anderson-Darling test, A2 = 6.4925, $p < 0.0001$; curve coefficients $\mu = 0.7059 \pm 0.0028$, $\sigma = 0.0937 \pm 0.0064$). In addition, a Principal Components Analysis, which estimates correlations by the Row-wise method, revealed no correlation among our three independent variables (age, region, profession; see **Supplementary Table 3**).

Multiple Regression

Next, to determine the effect of each of the variables of interest on participants' performance, we conducted a multiple regression analysis including all variables of interest and their interactions, $F(14,1113) = 9.0102$, $p < 0.0001$. The test revealed a significant contribution of each of the variables, with the strongest contribution being that of Profession. Effect tests: Age (F ratio 3.0971, $p = 0.0088$); Region (F ratio 3.2083, $p = 0.0070$); Profession (F ratio 17.9602, $p < 0.0001$). None of the interactions reached significance (all *p*s > 0.05). For Age, *post hoc* Tukey HSD tests revealed significantly lower performance by the 60 and older group compared with the 20-29-year-old group ($p = 0.0453$) and the 30-39-year-old group ($p = 0.0418$), respectively. In terms of Region, respondents in the Southeast performed significantly better than those in the Northeast ($p = 0.0315$). Finally, in terms of Profession, the Biological sciences group answered significantly better than all other groups (Exact sciences: $p = 0.0002$; Humanities: $p < 0.0001$; Health: $p = 0.0014$; Other: $p < 0.0001$), and the Other/retired/not working group performed significantly worse than all other groups (Exact sciences: $p = 0.0063$; Humanities: $p < 0.0001$; Health: $p < 0.0001$).

Analyses of Variance

To further assess effects within each variable, we conducted one-way Analyses of Variance. The main effect of Age was significant, $F(5,1122) = 6.36$, $p < 0.0001$, $\eta_p^2 = 0.03$, with participants in the 20–29 group responding best and individuals in the 60 and older group responding worst (**Figure 2**; see **Supplementary Table 4** for means and SEMs). The Levene's test for equality of variance was not significant ($p = 0.4021$), indicating homoscedasticity. Furthermore, *post hoc* Tukey HSD tests revealed that the 60+ group responded worse than the 20–29, the 30–39 and the 40–49 groups, respectively, and the 50-59 group responded worse than the 20–29 group (see **Supplementary Table 5**).

To assess the effect of Region, we excluded participants who did not declare their region of origin ($n = 24$). For the remaining participants ($n = 1,104$), the main effect of Region was also significant, $F(4,1099) = 3.10$, $p < 0.0150$, $\eta_p^2 = 0.01$, with participants from the Southeast obtaining the highest scores and individuals from the North obtaining the lowest scores (see **Supplementary Table 6**). The Levene's test for equality of variance was not significant ($p = 0.3837$), indicating homoscedasticity. No *post hoc* comparisons reached significance (see **Figure 3**).

Finally, the main effect of Profession was also significant, $F(4,1123) = 24.12$, $p < 0.0001$, $\eta_p^2 = 0.08$, with participants who declared working in the biological sciences (Bio) responding

TABLE 4 | Population by region in Brazil (IBGE, 2021) and in our study (n and % of total for each).

	Brazilian Population		Our study		Chi-square	p-value
	n	% of total	n	% of total		
Southeast	89,632.91	42%	756	67%	3.01	$p > 0.5$
Northeast	57,667.84	27%	154	14%	2.01	$p > 0.5$
South	30,402.59	14%	109	10%	0.32	$p > 0.5$
North	18,906.96	9%	44	4%	0.94	$p > 0.5$
Midwest	16,707.34	8%	41	4%	0.65	$p > 0.5$
Undeclared			23	2%		
Total Brazil	213,317.64	100%	100%	100%		

Chi-squared and associated p values revealing the regional distribution did not differ significantly between groups.

TABLE 5 | Survey.

Question	CA	%	Age	Region	Prof	SC
1. Despite weighing approximately 1.2 kg and having between 80 and 100 billion neurons, we only use 10% of our brain's capacity	F	45	$p < 0.0001$		$p < 0.0001$	NM
2. Structural differences between male and female brains are so obvious that any professional can identify a person's gender simply by looking at an image of their brain	F	17			$p < 0.0001$	NM
3. Alzheimer's disease can only be diagnosed after death. In life, behaviors can be identified through neuropsychological tests that suggest the presence of the disease	T	66				M
4. During meditation, our brains show alpha waves, a state of deep relaxation	T	69				M
5. Serotonin is a depression medication produced only in laboratories	F	95	$p < 0.0020$		$p < 0.0001$	M
6. The total number of neurons determines the power of our memory and general cognition	F	74			$p < 0.0001$	NM
7. Anxiety is caused by chemical disturbances in the brain	T	70	$p < 0.0307$			M
8. Every neuron stores different information	F	57			$p < 0.0001$	NM
9. We use our brains 24 h a day	T	93	$p < 0.0326$			NM
10. Magnetic Resonance Imaging can be used to see what people are thinking	F	94				M
11. There are critical or sensitive periods during childhood after which certain things become more difficult to learn, such as piano or languages	T	65	$p < 0.0032$			NM
12. Multiple Sclerosis can begin at any age	T	83		$p < 0.0008$		M
13. All stroke patients lose their speech	F	99		$p < 0.0018$	$p < 0.0273$	M
14. Drugs do not alter the brain's biochemical composition, but they do alter behavior	F	74	$p < 0.0027$		$p < 0.0109$	M
15. Cell death in Parkinson's disease causes motor symptoms such as freezing and tremors	T	90		$p < 0.0142$		M
16. Vaccines cause autism in developing children	F	99		$p < 0.0129$		M
7. Although we only remember small parts of our dreams, dreams are long and happen in "real time" relative to the events they represent	T	41		$p < 0.0234$		NM
18. Each region of the brain has a unique function	F	47	$p < 0.0166$		$p < 0.0001$	NM
19. Neuroplasticity, the nervous system's ability to change and adapt, ends after adolescence	F	87			$p < 0.0010$	M
20. Humans are the only living beings with consciousness	F	55	$p < 0.0094$		$p < 0.0099$	NM
21. Our imagination can create false memories; events we believe we experienced but never happened	T	94		$p < 0.0195$	$p < 0.0265$	M
22. Larger brains are smarter	F	93				NM
23. The best prevention against Alzheimer's disease is physical exercise	T	51			$p < 0.0093$	M
24. During sleep, our brain activity decreases	F	37			$p < 0.0026$	NM
25.IQ scores may change over time	T	84	$p < 0.0001$		$p < 0.0003$	NM
26. When we see different colors in a dress or sneakers, it is because we are using the dominant side of our brain (right vs. left)	F	39			$p < 0.0023$	NM
27. The period between 0 and 3 years of age is a very important period of neuronal growth and proliferation. For better performance in life, children must be exposed to all possible stimuli during this period, such as math, language and music	F	25	$p < 0.0240$			NM
28. Epilepsy is not contagious, but can be inherited	T	92				M
29. Using a tablet or cell phone during the first years of life can positively influence a child's development	F	77		$p < 0.0204$	$p < 0.0325$	M
30. During hypnosis, we completely lose consciousness	F	73			$p < 0.0001$	NM

The 30 survey statements listed in the order of presentation, which was the same for all participants. CA: correct answer (true or false); %: percent of patients who answered correctly; Age/Region/Prof: p-values for questions that differed based on Age, Region or Profession. SC: statement category (M: questions often covered in the media; NM: statements about classic neuromyths).

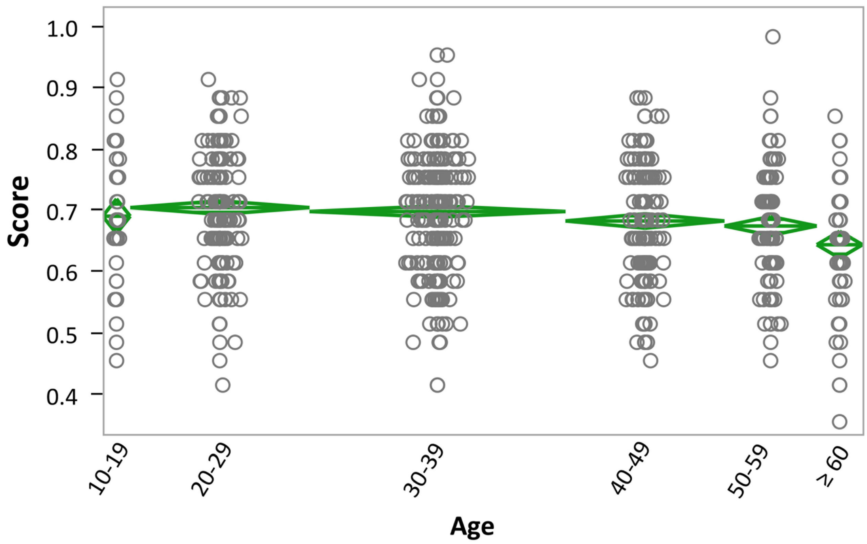

FIGURE 2 | Age × overall score. Overall score for participants in the different age groups: 10–19 years old, 20–29 years old, 30–39 years old, 40–49 years old, 50–59 years old, and 60 or older. Data are shown in mean diamond graphs, where the width of the diamond is directly proportional to the sample size, and the height corresponds to the variance. No intersection between diamonds implies rejection of the null hypothesis for an α error of 5%. The circle markers represent each participant's score.

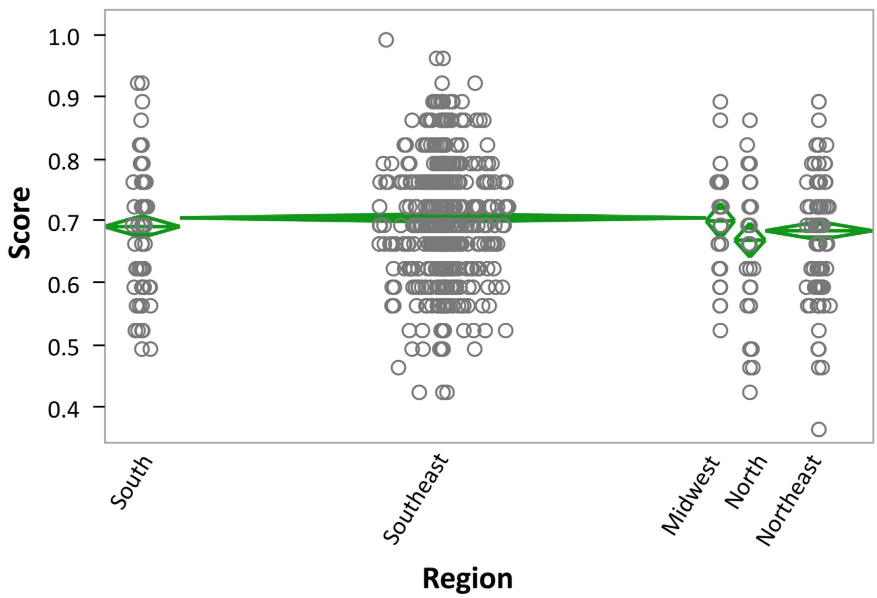

FIGURE 3 | Region × Score. Data are shown in mean diamond graphs, where the width of the diamond is directly proportional to the sample size, and the height corresponds to the variance. No intersection between diamonds implies rejection of the null hypothesis for an α error of 5%. The circle markers represent each participant's score.

best and individuals who declared 'other, retired or not working' (Other) responding worst (see **Supplementary Table 7**). The Levene's test for equality of variance was not significant ($p = 0.3617$), indicating homoscedasticity. Furthermore, *post hoc* Tukey HSD tests revealed that the Bio group performed significantly better than all others, while people in the exact sciences (Exa), humanities (Hum) and Health groups differed only from the Other group and not from each other (see **Figure 4** and **Supplementary Table 8**).

Next, we were interested in taking a closer look at effects within Region and Profession. First, we wanted to know whether Age made a difference in neuroscience-related knowledge in each of the six regions studied. This effect was significant in only three regions: Southeast, Midwest and Northeast.

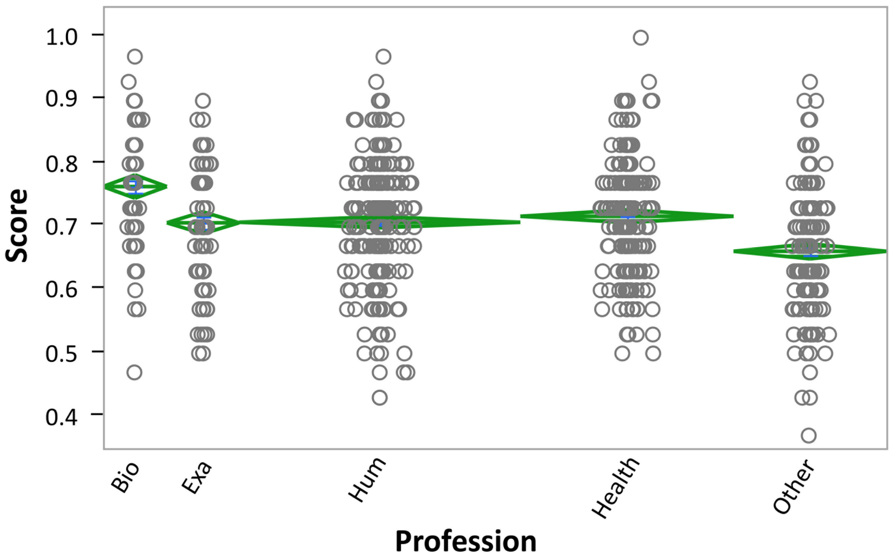

FIGURE 4 | Profession × overall score. Individuals reported studying or working in the areas of Biological Sciences (Bio), Exact sciences (Exa), Humanities (Hum), Health, or Other (other, retired, or not working). Data are shown in mean diamond graphs, where the width of the diamond is directly proportional to the sample size, and the height corresponds to the variance. No intersection between diamonds implies rejection of the null hypothesis for an α error of 5%. The circle markers represent each participant's score.

In the Southeast, scores decreased from youngest to oldest [$F(5,750) = 3.21$, $p = 0.007$, $\eta_p^2 = 0.02$; **Supplementary Table 9**], and *post hoc* Tukey HSD tests revealed that the 60 + group differed significantly from the 20-29 to 30-39 groups, respectively (**Supplementary Table 10**).

Similarly, in the Midwest, age groups followed a similar pattern, $F(4,36) = 3.79$, $p = 0.0113$ $\eta_p^2 = 0.30$, with the 20–29 group performing best, followed by the 30–39 group, then the 50–59 and 40-49 groups, and finally the 60 + group (see **Supplementary Table 11**). *Post hoc* Tukey HSD tests revealed that the 60 + group differed significantly from the 20–29 to 30–39 groups, respectively (see **Supplementary Table 12**).

Finally, in the Northeast, 20–29 year-olds answered best, followed by 40–49 year-olds and 30–39 year-olds, then 10–19 year-olds, 50–59 year-olds, and finally the 60 + group, $F(5,148) = 3.94$, $p = 0.0022$, $\eta_p^2 = 0.12$ (**Supplementary Table 13**). *Post hoc* Tukey HSD tests revealed that the 60 + group performed significantly worse than the 20–29, 30–39, and 40–49 groups, respectively (**Supplementary Table 14**).

We then investigated whether profession made a difference in each of the regions, and effects were significant for three regions as well: South [$F(4,104) = 2.90$, $p = 0.0255$, $\eta_p^2 = 0.10$], Southeast [$F(4,751) = 13.98$, $p < 0.0001$, $\eta_p^2 = 0.07$], and Northeast [$F(4,149) = 4.48$, $p = 0.0019$, $\eta_p^2 = 0.11$]. Thus, in two regions (Midwest and North), profession did not seem to influence neuroscience-related knowledge.

As seen in the overall analyses, people in the Other category performed worst in all three regions where profession had an effect. Also in line with the overall analyses, people in the Biological sciences group performed best in the Southeast and Northeast, while the other professions did not differ from each other (see **Supplementary Tables 15–18**). Interestingly, in the South, the Exact sciences group performed best, followed by Health, then Humanities, then the Biological group, and finally the Other group. Only one *post hoc* Tukey HSD test was significant, revealing that the Other group performed worse than the Exact sciences group ($p = 0.0439$; see **Supplementary Table 19**).

When we asked whether Age made a difference in neuroscience-related knowledge in each of the professions studied, no effects reached significance. Finally, a Pearson's multivariate regression analysis showed no significant correlation between participant performance and total years of schooling or total years in current profession.

Media Coverage Versus Classic Neuromyths

As mentioned in the introduction, prior to our analyses we hypothesized that respondents would perform better on statements about topics often covered in the media (e.g., vaccines, autism, child development and neurodegenerative disorders such as Alzheimer's and Parkinson's diseases) than on statements about common neuromyths (e.g., brain size and IQ, male vs. female brains). Thus, we divided the 30 statements into the two categories (see **Table 5**) and conducted a Multivariate analysis of variance (MANOVA), $F(76,1051) = 1.46$, $p = 0.0073$, which confirmed our hypothesis: overall, individuals performed better on the Media statements (overall mean = 0.83) than on neuromyths (overall mean = 0.56). See **Supplementary Tables 20–22** for means and SEMs for each of the variables.

In terms of age, $F(5,1122) = 2.43$, $p = 0.0333$, $\eta_p^2 = 0.01$, the 40–49 group showed the biggest discrepancy in performance between question categories, followed by the 60 + group, then the 50–59 group, the 30–39 group, 10–19 group and 20–29 group. The only significant *post hoc* Tukey HSD test showed that the 40–49 group differed significantly from the 20 to 29 group ($p = 0.0215$).

In terms of region, $F(4,1099) = 2.59$, $p = 0.0354$, $\eta_p^2 = 0.01$, the Northeast showed the biggest discrepancy, followed by the North, then the Southeast, the South and the Midwest. No *post hoc* comparisons reached significance.

Finally, in terms of profession, $F(4,1123) = 6.45$, $p < 0.0001$, $\eta_p^2 = 0.01$, the Other group showed the biggest discrepancy, followed by the Exact science group, then the Humanities, Health, and Biological sciences group. Three significant *post hoc* Tukey HSD tests showed that the Other group differed significantly from the Health ($p = 0.0030$), Humanities ($p = 0.0020$), and Biological sciences groups ($p < 0.0001$), respectively.

DISCUSSION

In order to test general knowledge about Neuroscience in a sample of Brazilian individuals from varied backgrounds, we created a 30-item questionnaire that aimed to cover a range of neuroscience topics as well as common neuromyths. Besides including questions previously asked by authors in other countries, we searched for the neuroscience-related questions that showed up most often in Google searches conducted in Brazil in Portuguese.

While participants overall had relatively good knowledge of some pathologies (e.g., stroke, epilepsy, Parkinson's Disease and Multiple Sclerosis), the role of serotonin and the concept of neuroplasticity, most participants endorsed classic neuromyths (the period between 0 and 3, left- vs. right-hemisphere dominance, and using only 10% of the brain). Overall, the percent of correct responses ranged from 17 to 99%, and there were important differences in performance based on age, region and field of study or profession.

In terms of age, the second youngest group (20–29-year-olds) performed best overall, while participants in the oldest group (60 and older) responded worst. This difference may reflect the fact that information (neuroscience-related and otherwise) has recently permeated environments most commonly frequented by younger folks, such as colleges/universities, and especially online sources, including social media platforms (Chudler and Bergsman, 2014; Babinski et al., 2018; Falk et al., 2013). In Brazil, internet use is highest among 18–29-year-olds (90–91%), and lowest among individuals 60 and older (38.7%), with numbers steadily declining with increasing age (IBGE, 2018).

In terms of location within Brazil, people in the Southeast performed best, while people in the North responded worst. This finding is in line with what we know about inequalities across Brazilian regions in terms of access to education, internet and other resources, which generally favor the South and Southeast and are worst in the North and Northeast (IBGE, 2021). However, while the quality of education is mostly better in the more favored regions (and average number of years of education is higher), we know that nowadays, much information is accessed online. Further, while internet access does vary across regions (IBGE, 2021), we know that internet use is high and widespread in Brazil (We are Social, 2020). Thus, if the quality of information accessed (online courses or websites with medical or scientific information) is generally good in quality, the internet should improve access to information for people with lower education levels, potentially narrowing the gap between groups. In this study we question the quality of online science information because of the number of non-science online portals in Brazil that publish this type of information (IGC, 2018) as well as the exponential growth of science course offerings in recent years that are not associated with well-established higher learning institutes (see Introduction). Alternatively, our data may reflect the fact that better education gives people the tools they need to filter online information properly and access better quality sources while ignoring others. Future studies should investigate these ideas in further detail.

Finally, in terms of profession, individuals who declared working in the biological sciences most often answered best (in 4 out of 5 regions) (Drummond and Fischhoff, 2017), consistently ahead of individuals in the exact sciences, humanities, health sciences, and those who declared 'other, not working or retired'. Surprisingly, individuals in the health sciences consistently answered below the biological sciences group and also did not differ significantly in performance from the exact sciences or humanities groups (Roffman, 2006; Gould et al., 2014; Goldenberg and Krystal, 2017). When we analyzed questions individually, the health group answered best on only one question (14: *Drugs do not alter the brain's biochemical composition, but they do alter behavior* - correct answer: FALSE) This finding was surprising, as we hypothesized that people in the health sciences would perform similarly to people in the biological sciences and did not expect their performance to be similar to that of people in the exact sciences and humanities (e.g., accountants and lawyers).

Interestingly, in two regions (North and Midwest), profession did not influence knowledge in neuroscience (i.e., people in the biological and health sciences knew just as much – or little – as people in the exact sciences, humanities, or other areas). Additionally, in the South, people in the exact sciences outperformed everyone else, and people in the biological sciences in that region performed in second-to-last place (see **Supplementary Table 19**). Thus, while people in the sciences performed better overall, this was not true across all regions. This finding suggests that education and training in different fields may differ across regions and Brazil. This is another interesting area for future research.

Overall, six of the nine questions that participants answered best (90% correct or higher) had to do with pathologies, disorders or treatments (Q13 – Stroke, 16 – Vaccines, Q5 – Serotonin and Depression, Q10 – Magnetic Resonance Imaging, Q28 – Epilepsy, and Q15 – Parkinson's Disease; see **Table 1**), while five of the seven with the lowest scores (50% correct or worse) had to do with brain anatomy, overall function or development (Q18 – brain regions, Q1 – we use 10% of our brain, Q26 – hemispheric dominance, Q27 – critical periods and Q2 – male vs. female brains). One possible explanation for the discrepancy between types of knowledge is that it may be easier to access valid sources of information regarding health issues, while anatomy and physiology are most often learned in directed forms of study (i.e., courses; see also Betts et al., 2019). Furthermore, misrepresentations about anatomy and physiology may easily appear in entertainment media (e.g., series and films that talk about the use of 10% of the brain, online news that test whether people see different colors on a dress or sneakers and claim the answer depends on hemispheric dominance) (Brainard and Hurlbert, 2015; Gegenfurtner et al., 2015; Lafer-Sousa et al., 2015; Michel, 2015; Feitosa-Santana et al., 2018).

It is interesting to observe that while most people knew that larger brains do not mean smarter brains (Q22), other classic neuromyths were still prevalent (Q1, Q26 and Q2; see **Table 5**). And while most correctly answered that we use our brains 24 h a day (Q9), most incorrectly responded that brain activity decreases during sleep (Q24). The notion that larger brains are smarter (Q22) may be considered an "older" myth that people may have become familiar with when studies regarding brain evolution and the encephalization quotient first appeared a few decades ago (Deaner et al., 2007). Because these notions are somewhat older, over the years laypeople may have been exposed to more updated information that may have appeared in the media as curiosities (e.g., it's not the size or number of neurons that matter, but our synapses or connections; or, Einstein's brain was not that large after all! Salvatori, 1999; Falk, 2009; Hines, 2014). On the other hand, the notion that some people use one hemisphere more than the other (i.e., some people are predominantly "left- or right-brained") may have been reinforced more recently by viral phenomena such as "The Dress" (Lafer-Sousa et al., 2015).

When we divided our statements into those most often covered in the media versus more common neuromyths (see **Table 5**), we discovered that performance was significantly better on the media statements across groups, as predicted. While information can often be misconstrued in the media, it seems like some correct information does get through; furthermore, the media may also reinforce some neuromyths, as discussed above. Overall, the data suggest that neuromyths continue to be hard to eliminate across people from different walks of life.

Perhaps one of the most controversial issues tested was question 16: *Vaccines cause autism in developing children* (correct answer: FALSE). This neuromyth has invaded the media and taken hold of communities from all cultural and socioeconomic levels worldwide, with serious global health consequences (anti-vaccination movements, etc.) (Chiou and Tucker, 2018; Lavorgna et al., 2018). Great efforts have been made to tear this myth down, and we were pleasantly surprised to see that overall, it was the second ranked question, with participants answering with 99% accuracy. However, this question was influenced by region, with the North answering worst, suggesting there is still some work to be done in regions where quality education is not as readily available.

Another timely issue was presented in question 29 – *Using a tablet or cell phone during the first years of life can positively influence a child's development* (correct answer: FALSE). Interestingly, this was the only question where people in the humanities group answered best, followed by the Bio and health groups, and then the Other and exact groups. It is unclear why the humanities group would answer best, but since it is a timely topic that affects anyone caring for children, it follows that people from all areas would be interested in learning more about this issue.

To make sure the differences among groups did not reflect other variables intrinsic to the groups sampled, we conducted a Pearson's multivariate regression analysis, which showed no significant correlation between participant performance and total years of schooling or total years in current profession. Given that overall knowledge in neuroscience was generally low and that several respondents declared having completed several graduate-level courses (18+ years of education), this likely suggests that graduate programs in the neurosciences or related areas are limited in quality and/or effectiveness. Indeed, more years of study or work do not guarantee greater knowledge in neuroscience, even for those in the areas of health or biological sciences. Furthermore, the finding that Age did not influence Profession corroborated this finding: within each profession, chronological age (which should be strongly correlated with years of education and experience) did not influence neuroscience-related knowledge.

While one of our aims was to include questions identified as having raised the interest of the target population, a few questions may have been particularly difficult, given the nature of the topic or the way in which they ere worded. We noticed this only *a posteriori*, and the fact that most groups answered below chance on those questions supports our assumptions and precludes us from making any observations regarding group effects. The first of these was question 2: *Structural differences between male and female brains are so obvious that any professional can identify a person's gender simply by looking at an image of their brain (correct answer: FALSE)*. Structural and functional brain differences between the sexes have been reported in several academic publications, albeit in the context of group effects that considered large groups of participants. More recently, studies have argued that intragroup differences (women vs. other women or men vs. other men) are larger than intergroup ones (men vs. women), suggesting female or male structural characteristics cannot be identified on individual brain scans (Joel, 2011; Ingalhalikar et al., 2014). This last piece of information, however, which includes knowledge about the expertise of neuroimaging professionals, is likely beyond the scope of knowledge of people who are not specialists in this area or who have not done research specifically within this topic. Thus, answering this question incorrectly may not be a fair indicator of the quality of higher education or freely available sources of neuroscientific information.

Similarly, most groups answered below chance on question 17: *Although we only remember small parts of our dreams, dreams are long and happen in "real time" relative to the events they represent* (correct answer: TRUE). The original idea with this question was to tear down the myth that dreams represent signs of the divine, insights of future events, or symbolic clues from other worlds. A correct interpretation is that dreams are one way our brains process acquired information and crystalize memories (Wamsley, 2014). However, since the area of dreams is a very specific area of research that most people (even those in the health or science areas) may not have contact with, question 17 may also not be very informative.

Finally, we also had doubts about question 27: *The period between 0 and 3 years of age is a very important period of neuronal growth and proliferation. For better performance in life, children must be exposed to all possible stimuli during this period, such as math, language and music (correct answer: FALSE).* The wording in this question may have led to errors, as it may contain a "catch": the question speaks specifically of stimuli such as math, language and music – which would not result in any measurable benefit during these early years, considering children have not completely developed more basic functions such as vision, audition and motor skills. However, this may be confusing, since it is undeniable that various types of stimuli during this period are positive and necessary for normal development. While we tried to emphasize the insignificant (or even negative effect) excessive stimulation could have during this period, in retrospect, the question may not have adequately captured this idea. Thus, participants may have responded incorrectly based on some correct knowledge (i.e., that age-appropriate stimulation during the first three years of life can have a positive effect on development).

While yielding relatively high overall scores, two additional statements may raise questions: 10 (*Magnetic Resonance Imaging can be used to see what people are thinking*), and 11 (*There are critical or sensitive periods during childhood after which certain things become more difficult to learn, such as piano or languages*). A total of 94% of respondents indicated that statement 10 is False (which was the answer we intended to elicit). While MRI technology can reveal a lot about relative engagement of different brain regions on specific tasks of interest, it is not a method that allows us to read complex thoughts verbatim (as sometimes depicted in films or series) or even determine indirect mental states (e.g., whether someone is guilty, as in the proposed use of fMRI in a court of law). Thus, our goal with that statement was to assess whether individuals knew the relative limitations of that technology. For statement 11, 65% of respondents indicated it was true (our intended answer). While it may have been better to use only the term "sensitive," the term "critical" is older and probably more well-known, which is why we chose to keep the statement in that form ("critical or sensitive"). And, while controversy exists regarding how determinant such periods are for learning specific skills, little doubt exists in the scientific community that neuroplasticity gradually decreases and that this is likely linked to sensitive periods.

It is important to note that our study design requires that people be literate and have access to the internet. Thus, while we obtained responses from a large sample of Brazilians from all five geographical regions, age groups and several different professions, our sample does not represent the 11 million Brazilians over the age of 15 who are illiterate (EBC, 2020). Also, internet use is not the same across regions: a study from 2018 by the Brazilian Institute for Geography and Statistics (IBGE) found interregional differences in internet use (81.1% and 78.2% of people living in the Southeast and South use the internet, compared with 64.7% and 64% of people in the North and Northeast, respectively) (Markram, 2013). Our study also requires respondents to be interested in the topic and be motivated to respond, as all answers were voluntary. Furthermore, the method of data collection used in this study is known as snowball sampling, meaning we sent the survey to our contacts, who in turn shared it with their own contacts. While this type of sampling has the advantage of increasing reach (i.e., participants are more likely to respond when invited by people they know), this could create a non-random sample that may not perfectly generalize to the population at large. Thus, while online surveys have the advantage of quickly reaching many people in different locations, they are limited by the considerations listed above. While a design targeting specific populations (including people less interested in the topic who may not participate voluntarily) could reach individuals not included in the current survey, such designs carry additional methodological constraints (e.g., how to interpret responses from people who felt pressured to respond, such as in a classroom?). Future studies should explore how to obtain a more random sample while avoiding these additional experimental limitations.

CONCLUSION

Access to quality information and accurate knowledge about how the brain and nervous system work are essential parts of constructing a better-informed society. Such access can also help people better take care of their own health, as well as become better professionals, particularly in the areas of health (e.g., nurses and doctors), biological sciences, or even education.

A growing interest in Neuroscience-related knowledge in recent years has led to an exponential growth in the amount of related information (correct or not) made available online as well as the market for Neuroscience-related courses in Brazil. Despite this growing interest and course availability, Brazilians from all walks of life show poor knowledge in this field. We observed this even among people studying or working in the areas of biological or health sciences, and even among those reporting several years of graduate education or professional experience, suggesting much work needs to be done to improve the quality of (neuro)science-related course options. While overall, participants seemed to know more about themes that are often presented in the media, they all displayed high endorsement of common neuromyths (e.g., left- vs. right-hemisphere dominance, and using only 10% of the brain). We also observed differences among Brazilian regions, which reflect long-standing inequalities in terms of access to quality education and other resources. Thus, professionals seeking to improve the quality of scientific content and communication (in courses or otherwise) may begin by focusing on ways of combatting neuromyths and developing ways of reaching individuals in the health sector as well as those living in disadvantaged regions. To the best of our knowledge, this is the first study testing these questions in such a large sample of Brazilians from all regions and several walks of life. We hope future studies further explore these questions and others that were raised here and remain unanswered.

DATA AVAILABILITY STATEMENT

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

ETHICS STATEMENT

Ethical review and approval was not required for the study on human participants in accordance with the local legislation and institutional requirements. The patients/participants provided their written informed consent to participate in this study.

AUTHOR CONTRIBUTIONS

FP and ES conducted the word searches and created the survey. AA conducted the statistical analyses. FP, ES, and AA drafted the manuscript. All authors distributed the survey among their personal and professional contacts, reviewed and discussed the findings, and reviewed and approved the final manuscript.

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SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fnhum.2022.798967/full#supplementary-material

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Neuroscience Education Begins With Good Science: Communication About Phineas Gage (1823–1860), One of Neurology's Most-Famous Patients, in Scientific Articles

*Stephan Schleim**

Faculty of Behavioral and Social Sciences, Theory and History of Psychology, Heymans Institute for Psychological Research, University of Groningen, Groningen, Netherlands

Phineas Gage is one of the most famous neurological patients. His case is still described in psychology textbooks and in scientific journal articles. A controversy has been going on about the possible consequences of his accident, destroying part of his prefrontal cortex, particularly with respect to behavioral and personality changes. Earlier studies investigated the accuracy of descriptions in psychology textbooks. This is, to my knowledge, the first analysis of journal articles in this respect. These were investigated with regard to four criteria: Description of (1) personality changes, (2) psychopathy-like behavior, (3) alternative explanations besides the immediate brain damage, and (4) Gage's recovery. 92% of articles described personality changes, 52% of a psychopathy-like kind; only 4% mentioned alternative explanations and 16% described Gage's recovery. The results are discussed in the light of the available historical evidence. The article closes with several suggestions on improving science communication about the famous case.

Keywords: brain damage, ventromedial prefrontal cortex, neurorehabilitation, neuroplasticity, science communication, neuroethics, neuropsychology, phrenology

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Analía Arévalo,
University of São Paulo Medical School, Brazil

Reviewed by:
Sean Commins,
Maynooth University, Ireland

Correspondence:
Stephan Schleim
s.schleim@rug.nl

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INTRODUCTION

Phineas Gage is one of the most famous patients in the history of neurology, neuropsychology, and clinical neuroscience. On September 13, 1848, the then 25-year-old railroad worker prepared an explosion south of the village of Cavendish, Vermont (United States). When the blast was triggered accidentally, it propelled a heavy iron rod through his skull, irreversibly destroying part of his frontal lobe. Gage's survival invited investigation and discussion by many medical doctors, brain researchers, and psychologists ever since. And Gage did not only survive: He reportedly stayed conscious and responsive as colleagues brought him home and John M. Harlow, the local physician, started treatment (Harlow, 1848). What keeps fascinating researchers until the twenty-first century are, first, personality changes due to brain damage, and, secondly and more recently, the possibility of Gage's recovery (Macmillan, 2008; Macmillan and Lena, 2010). Only recently, his case was chosen as the first of six "essential landmark case reports" for neuropsychiatry (Benjamin et al., 2018). An increasing interest since the 1990s can be also seen in books (**Figure 1**).

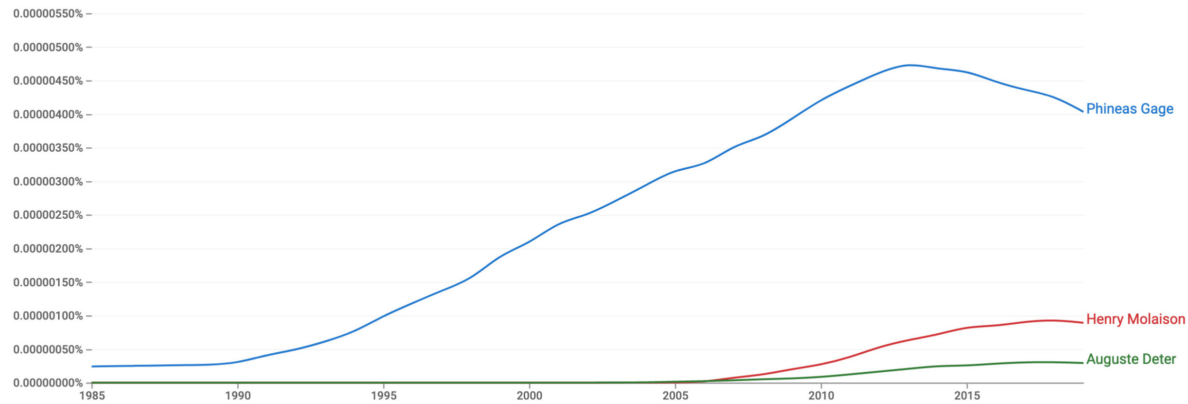

FIGURE 1 | This Google Ngram for English books from 1985 to 2019 shows a steeply increasing interest in Gage's case since the early 1990s (blue line). Two of the other "essential landmark case reports" discussed by Benjamin et al. (2018), Auguste Deter and Henry Molaison, are shown for comparison (green and red line, respectively). The other clinical cases discussed by these authors (Louis Victor Leborgne and Solomon Shereshevsky) received less attention in English books (not shown on the graph). Source: https://books.google.com/ngrams.

The aim of this Research Topic is to improve neuroscience education for the public[1]. Neuroscience education relies on good science communication, that is, that knowledge about the brain as well as its limitation is disseminated in a reliable, comprehensive, and correct way. Earlier reports suggested that the common account that the accident transformed Phineas Gage from a reliable foreman into a psychopath is not based on historical facts, or at least grossly exaggerated (Macmillan, 2000, 2002; Kihlstrom, 2010; Schleim, 2012). Malcom Macmillan, who compiled and reviewed the available historical evidence in detail, summarized such descriptions as follows:

> "The composite of modern writers has the accident transforming this Phineas into a restless, moody, unpredictable, untrustworthy, depraved, slovenly, violently quarrelsome, aggressive and boastful dissipated drunken bully, displaying fits of temper, and with impaired sexuality. He is a waster: unwilling to work and unable to settle down. He spends most of the rest of his life in traveling circuses or drifting around fairgrounds to exhibit himself as a human freak, and dies penniless" (Macmillan, 2008, p. 838).

A review of psychology textbooks from the late twentieth and early twenty-first century found many inaccuracies and omissions (Macmillan, 2000; Griggs, 2015). To my knowledge, no one thus far investigated the case's representation in scientific journal articles. Is this relevant? This issue is not just about scientific accuracy, a value of its own. As we have seen, Gage's accident still plays a prominent role in medical and psychological education; it is also still featured in public media, after more than 150 years[2]. More importantly, it may inform patients and their relatives about the possible impact of (prefrontal) brain damage and the chances of recovery. The description that Gage was irreversibly turned into a psychopath (or anything near enough) might stigmatize patients and their families and even lead to a self-fulfilling prophecy, if people are then excluded and denied treatment as hopeless cases. Earlier research on science communication has shown that in particular clinical populations are likely to link information about the brain to their personality (O'Connor and Joffe, 2013, 2014; Davis, 2020). In extreme cases, some might even demand to put these allegedly dangerous patients into preventive detention, a possible future scenario described by Raine (2013).

For a more reflective investigation, descriptions about Gage's accident, its psychological consequences, and his recovery can be discussed with respect to the following three theoretical concepts: (1) Neurodeterminism; (2) localizationism; and (3) neurorehabilitation. The first means that people's behavior is primarily or solely determined by their brain, not by their situation or environment; the second means that personality traits predisposing people to show certain behaviors can be linked to identifiable areas in the brain[3]; and the third means that people can (at least partially) recover from brain damage, enabled by neuroplasticity and a facilitating environment. To understand science communication about Phineas Gage, I investigated the case's description in scientific journal articles, as described in the next section. Characteristic quotes are provided in **Supplementary Material**. I will summarize the findings in the

[1] https://www.frontiersin.org/research-topics/16682/how-to-improve-neuroscience-education-for-the-public-and-for-a-multi-professional-audience-in-differ#overview

[2] An excellent example is Sam Kean's article in *Slate*, https://slate.com/technology/2014/05/phineas-gage-neuroscience-case-true-story-of-famous-frontal-lobe-patient-is-better-than-textbook-accounts.html (accessed June 30, 2021). A more recent example is Katie Serena's article for *all that's interesting* of October 2021 which even described Gage's case as having helped to "give birth to modern neuroscience," https://allthatsinteresting.com/phineas-gage (accessed February 9, 2022).

[3] Note an important difference between the first two: If localizationism is true, neurodeterminism is also true (at least with respect to personality traits), but not the other way around. Localizationism predicts that people with damage in the same areas have (more or less) the same deficits. But neurodeterminism could be true without it: Then the personality traits or behaviors would depend on the functioning of larger networks in a more holistic fashion, which would make the patients' expected deficits more diverse and also make it seem more likely that lost functions can be compensated by other parts of the nervous system. It goes without saying that such theoretical thoughts are limited in that in actual clinical cases no two brain lesions will be *exactly* alike.

discussion and close with a suggestion on how to communicate better about Gage in the future.

INVESTIGATION

Journal articles covering Phineas Gage were identified on the *Web of Science*, a popular science database featuring more than 80,000,000 records in more than 20,000 journals[4]. A topic search yielded 59 records published from 1994 to 2020 of which 32 were eligible for analysis[5]. These articles were investigated with respect to the described personality changes, particularly whether they referred to psychopathy-like behaviors such as pathological lying, aggressiveness, and violence, and recovery of Gage after the accident; it was also investigated whether they addressed other possible causes of his personality change, such as post-traumatic stress, physical disfigurement, or progressive brain disease.

The result of the analysis is that seven out of the 32 articles are historical overviews which are difficult to assess according to the proposed criteria (Barker, 1995; Neylan, 1999; Macmillan, 2008; Wilgus and Wilgus, 2009; Macmillan and Lena, 2010; Schleim, 2012; Griggs, 2015). These publications quote and compare various historical sources, point out uncertainties, and sometimes even critically appraise that some authors might have seen Gage's symptoms in the light of the theories they favored. For example, Barker (1995) discusses that Harlow, Gage's physician, was inclined toward phrenology, an early and extreme form of localizationism, while the renowned Harvard surgeon Henry J. Bigelow, with whom Gage spent some two months, roughly a year after the accident, was a known antilocalizationist. This is important context information when reading that the latter declared Gage completely restored, physically as well as mentally (Bigelow, 1850), while Harlow described the allegedly permanent personality changes that are still frequently quoted in the contemporary literature (Harlow, 1868).

The remaining 25 articles, though, could be assessed according to the proposed criteria (**Supplementary Table 1**). Almost all of them (23 of 25, or 92%) wrote that Gage's personality changed after the accident. This is unsurprising, given that this is what makes the case psychologically interesting, that it links brain, mind, and behavior already in a time when modern brain imaging was unavailable. The two exceptions were focusing on the anatomical details (Kelley et al., 2007) or only superficially referred to Phineas Gage, in spite of mentioning his name in the title (Dunbar, 2009). About half of the articles (13 of 25, or 52%) emphasize psychopathy-like behaviors like frequent lying, insulting people, and/or violence. Many did quote from Harlow's original paper describing personality changes in that direction (Harlow, 1868), but without mentioning other sources or that this evidence is circumstantial.

Two articles explicitly addressed psychopathy in the context of brain damage similar to Gage's (Thiebaut de Schotten et al., 2015; Reber and Tranel, 2017) and a third one addressed the topic, but concluded "that the supposed psychopathic traits are not evident" in Gage's case (Kotowicz, 2007: 116). This was also the only paper (1 of 25, or 4%) addressing physical disfigurement and the possibility of social exclusion as an explanation of Gage's immoral behavior. Finally, a small minority of the articles (4 of 25, or 16%) reported that Phineas Gage found a new job after the accident and had a somewhat stable life. After this brief summary of the results, they will be discussed in more detail the next section.

DISCUSSION

The aim of this article is to provide an overview of the presentation of Phineas Gage's accident and its consequences, particularly with respect to his personality, in scientific journal articles. As mentioned in the introduction, earlier publications suggested that his case is not always presented accurately and, in particular, that Gage's personality changes were sometimes grossly exaggerated (Macmillan, 2000, 2002; Kihlstrom, 2010; Schleim, 2012). An analysis of psychological textbooks found that their descriptions should be improved in several respects (Macmillan, 2000; Griggs, 2015). This article is, to my knowledge, the first overview of scientific journal articles covering Phineas Gage.

The vast majority of the articles described that Gage's personality changed as a consequence of the accident, irreversibly damaging part of his prefrontal cortex[6]. In my view it *is* likely that he behaved differently afterward. Unfortunately, though, no complex neuropsychological investigation was available in 1848 and Harlow's detailed account was compiled some 20 years after the event, eight years after Gage's death, and provides only a very general and in many respects vague account of his personality (Harlow, 1868). This is in stark contrast to Bigelow's portrayal of Gage as fully recovered (Bigelow, 1850). As mentioned above, both could have been influenced by their belief in localizationism or antilocalizationism (Barker, 1995). Furthermore, Bigelow, the Harvard surgeon, investigated Gage roughly a year after the accident, most of which the patient had spent with his family for recovery after his health state had become stable. By that time, his personality and behavior might have improved, at least partially. This assumption makes more sense when considering alternative effects on Gage's personality and behavior: We now know that lesser accidents and illnesses than what the young railroad worker went through can have traumatic effects. Actually, many of Gage's contemporaries imagined him not to survive his injury and even his family is reported to have begged Harlow to let him die (Barker, 1995). And while Kotowicz's (2007) suggestion that Gage's physical disfigurement might have led to stigmatization and social exclusion seems exaggerated now that photographs of

[4]https://clarivate.com/webofsciencegroup/solutions/web-of-science/ (accessed June 30, 2021).

[5]The topic search with the phrase "Phineas Gage" covered titles, abstracts, and keywords on the *Web of Science*. Excluded were book reviews, meeting abstracts, letters to the editor, and articles not published in English.

[6]There has been a controversy on which brain regions precisely were damaged. Damasio et al. (1994), who made Gage's case more popular in the recent decades, investigated his skull and concluded that his ventromedial prefrontal cortex must have been destroyed bilaterally. Later reconstructions concluded, though, that only the left part could have been damaged (Ratiu et al., 2004; Van Horn et al., 2012). This discussion is relevant to localizationism, but not for the main topic of this article. It should be noted, though, that Harlow's surgical treatment and the ensuing infection is likely to have damaged additional brain tissue (Harlow, 1848).

the recovered patient have been found (Wilgus and Wilgus, 2009; Macmillan and Lena, 2010), the young man *might* have looked like what some of us would call a "zombie," immediately after the accident, with part of his skull shattered, his left eye permanently damaged, and after Harlow's surgery (Harlow, 1848). This might, in turn, have influenced how Gage's friends and former employees reacted to him. The latter reportedly turned down his request to work for the railroad company again, which might have provoked the impulsive behavior and insults Harlow reported (Harlow, 1868).

We will probably never know the whole truth. But the perspective we take will influence the plausibility of neurodeterminism, as described above. What is more based on historical facts, though, is Gage's recovery. In contrast to some descriptions, he did find new jobs, for example at a farm where he worked with horses. After he moved to Chile, he worked as a stagecoach driver, following a rigorous working scheme, dealing with passengers and caring for the horses (Barker, 1995; Macmillan, 2000, 2002). On the basis of this evidence and more recent knowledge of neurorehabilitation, Macmillan and Lena hypothesize that such highly structured environments, i.e., animals are in need of regular care, traveling schedules have to be followed reliably, facilitated Gage's recovery (Macmillan, 2008; Macmillan and Lena, 2010). They also found the historical record of a doctor in South America who stated that Gage "was in the enjoyment of good health, with no impairment whatever of his mental faculties" (Macmillan and Lena, 2010, p. 648). It goes without saying that this witness did not know Gage before the accident, just like Bigelow. But we may assume that these medical experts would have noticed signs of pathological lying, aggressiveness, or violence.

This analysis is limited in several respects. First of all, I only investigated journal articles listed on the *Web of Science*. Much of science communication takes place in book chapters in edited volumes and non-fiction books written for broader audiences (**Figure 1**). Authors might have fewer constraints in such media, such as strict word limits, and thus describe cases in more detail and from more perspectives than is possible in journal articles and psychology textbooks. Secondly, my criteria are pragmatic, about personality changes in general, psychopathy-like changes more particularly, alternative perspectives, and Gage's recovery. They can be improved to allow a more in-depth analysis of the articles, but still yielded meaningful differences (**Supplementary Table 1**). With more detailed criteria, it might also be possible to classify the seven "historical overviews" better (see **Supplementary Material**). Finally, the concepts of psychopathy and psychopathy-like behavior were used in a vague manner here. It should be noted, though, that psychopathy is not a recognized category in the Diagnostics and Statistics Manual of the American Psychiatric Association (2013), although it is used by forensic psychologists and psychiatrists, and that there is an ongoing discussion about its precise definition (e.g., Pickersgill, 2014; Schleim, 2015).

In a similar review, Griggs found that 21 out of 23 introductory psychology textbooks included a discussion of Gage's case and described it in a generally accurate way, but that only about half of them addressed his subsequent history and recovery (Griggs, 2015). Based on this analysis of scientific journal articles, science communication about Phineas Gage can be improved in several ways: First, different historical sources should be mentioned (particularly Bigelow, 1850; Harlow, 1868), whenever possible, and it should be stated that evidence about Gage's personality changes is scarce, circumstantial, and controversial. Second, it should be recognized that (at least transitory) psychological trauma and physical disfigurement might have played a role, too, and that Gage suffered from severe infection, fever, and coma shortly after the accident as well as progressive brain damage causing epileptic fits in the long run, which is also the official cause of his premature death in 1860 (Harlow, 1868). Third, Gage's (at least partial) recovery should be mentioned, to also give patients presently suffering from similar brain damage and their relatives more hope and to stimulate new developments in neurorehabilitation.

DATA AVAILABILITY STATEMENT

The original contributions presented in the study are included in the article/**Supplementary Material**, further inquiries can be directed to the corresponding author/s.

AUTHOR CONTRIBUTIONS

The author confirms being the sole contributor of this work and has approved it for publication.

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SUPPLEMENTARY MATERIAL

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Neuroscience Outside the Box: From the Laboratory to Discussing Drug Abuse at Schools

Thereza Cristina Machado do Vale[1,2], Luana da Silva Chagas[1,2], Helena de Souza Pereira[3], Elizabeth Giestal-de-Araujo[2], Analía Arévalo[4†] and Priscilla Oliveira-Silva Bomfim[1,2†]*

[1] NuPEDEN, Nucleus for Research, Education, Dissemination and Neurosciences Popularization, Department of Neurobiology and Program of Neurosciences, Institute of Biology, Federal Fluminense University, Niterói, Brazil, [2] Department of Neurobiology and Program of Neurosciences, Institute of Biology, Federal Fluminense University, Niterói, Brazil, [3] Department of Molecular and Cell Biology, Institute of Biology, Federal Fluminense University, Niterói, Brazil, [4] Department of Experimental Surgery, University of São Paulo Medical School, São Paulo, Brazil

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***Correspondence:**
Priscilla Oliveira-Silva Bomfim
priscillaos@id.uff.br

† These authors share senior authorship

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One of the effects of the current COVID-19 pandemic is that low-income countries were pushed further into extreme poverty, exacerbating social inequalities and increasing susceptibility to drug use/abuse in people of all ages. The risks of drug abuse may not be fully understood by all members of society, partly because of the taboo nature of the subject, and partly because of the considerable gap between scientific production/understanding and communication of such knowledge to the public at large. Drug use is a major challenge to social development and a leading cause of school dropout rates worldwide. Some public policies adopted in several countries in recent decades failed to prevent drug use, especially because they focused on imposing combative or coercive measures, investing little or nothing in education and prevention. Here we highlight the role of neuroscience education as a valid approach in drug use education and prevention. We propose building a bridge between schools and scientists by promoting information, student engagement and honest dialogue, and show evidence that public policy regulators should be persuaded to support such science-based education programs in their efforts to effect important positive changes in society.

Keywords: neuroscience, education, public policies, science outreach, drug education

INTRODUCTION

The abuse of substances, illicit or not, is a worldwide health problem that deserves immediate attention. According to the United Nations Office on Drugs and Crime, millions of drug users worldwide also have depression, anxiety or suicidal intentions (UNODC, 2021). Secondary consequences of drug abuse include a heightened risk of contracting hepatitis B/C and HIV and death or injuries from vehicle accidents (Olfson et al., 2018; Glei and Preston, 2020). The combined costs of these possible consequences most likely surpass the cost of most government prevention programs. In low- and middle-income countries, huge social inequalities worsen the issue and highlight the inefficiency of public policies that focus more on fighting rather than preventing drug abuse (UNODC, 2021).

Here we address neuroscience's potential to contribute to this discussion (World Health Organization [WHO], 2004), especially in schools, a privileged environment for knowledge dissemination (Faggiano et al., 2005). Activities and programs that engage scientists, students, families, school teachers/staff, physicians and therapists engaged in rehabilitation, and members of the community or neighborhood are much more likely to have positive results than actions that aim to instill fear (i.e., fighting rather than preventing). We emphasize the importance of making the information engaging and accessible to the target audience by considering their prior knowledge and cultural/socioeconomic level, as well as creating public policies that promote and support such actions.

THE BRAIN UNDER (DRUG) PRESSURE

The use of substances such as alcohol, marijuana, cocaine and opioids, among others, usually starts during adolescence, a period of rapid brain circuit maturation that is highly influenced by genetic and environmental factors (Fuhrmann et al., 2015; LeNoue and Riggs, 2016; UNODC, 2021). The need for independence, identity formation and peer acceptance (Bauman and Phongsavan, 1999; UNODC, 2021) make adolescence a critical period of physiological and social development characterized by an increase in risk-taking behaviors driven by the pursuit of quick rewards (Botvin and Botvin, 1992; Willoughby et al., 2013; UNODC, 2021). These behaviors are associated with an immature prefrontal cortex, an area of the brain responsible for evaluation and planning, decision making and impulse control. Since this region remains highly sensitive to external influences until around 20 years of age, drug use during adolescence can lead to significant functional and structural brain changes. These changes, in turn, exacerbate the natural "imbalance" among the regulatory frontal circuits (whose maturation is delayed relative to the cortico-limbic circuits), potentially leading to long-term problems in the areas of emotional control and reward feedback (Gogtay et al., 2004; Arain et al., 2013; Ernst, 2014), as well as an increased risk of developing drug addiction. Furthermore, adolescents seem unconcerned with the possible consequences of using psychoactive substances and a tendency to believe they are in control and could discontinue use at any point if they wish (Bauman and Phongsavan, 1999). Importantly, child drug use is associated with the later use of potentially more harmful drugs, such as heroin and cocaine (Fletcher et al., 2008).

Studies show that an individual's family may be the root of substance use/abuse, since children and adolescents often look up to their parents and caregivers (Flay et al., 1994; Biederman et al., 2000). Factors that increase children's risk of becoming smokers include free access to cigarettes (Kim et al., 2009), having parents who ask them to bring them cigarettes (Hill et al., 2005) or are heavy smokers (Hill et al., 2005), and being exposed to smoking by others over a period of years (Mays et al., 2014). Furthermore, observing relatives' social behavior may send children the message that enjoyment is directly related to alcohol consumption (Ryan et al., 2010; Smit et al., 2018).

Alcohol abuse in young people is highly influenced by underlying levels of stress, anxiety, and depression, and can increase the chances of dropping out of school (Henkel, 2011; World Health Organization [WHO], 2014; Tice et al., 2017; Valkov, 2018). Moreover, legal and illegal drug consumption profoundly impacts young people's mental health, a focus of great concern among health professionals, families, and public institutions (Galvão et al., 2017). These issues have become particularly important in recent months, since the beginning of the COVID-19 pandemic, which among other social disruptions, led to school closures (Cowie and Myers, 2020; Chaffee et al., 2021).

In many countries around the world, including Brazil, depression is higher among individuals who abuse alcohol, one of the first drugs that adolescents have contact with. Depression, in turn, can lead to suicidal ideation (Kim, 2017; Rehan et al., 2017; McHugh and Weiss, 2019). Data have shown that 5% of Brazilians have attempted suicide at least once and that 24% of those cases are associated with alcohol consumption. Importantly, suicide is the 3rd cause of death globally and Brazil is among the top 10 countries with the highest suicide rates (Laranjeira et al., 2012; Barbosa and Teixeira, 2021).

THE IMPACT OF DRUG ABUSE ON EDUCATION

In Brazil, government data suggest that drug use is prevalent among both private and public school students, with public school students usually consuming heavier, lower-cost drugs. Interestingly, students in both groups lack an understanding of substance composition, as well as the risks and consequences of drug use (Laranjeira et al., 2012).

In terms of neurological effects, evidence indicates that young people who binge drink or consume heavy amounts of alcohol show reduced gray matter in frontolateral and temporal cortices, as well as reduced white matter development in the corpus callosum and pons, which may increase the risk of developing alcohol-related disorders, as mentioned above (Squeglia et al., 2015; Cservenka and Brumback, 2017). Drug use during this period of life can also disrupt motivation, memory, and learning (Fowler et al., 2007), all functions essential during the educational process.

Excessive alcohol consumption also affects brain regions involved in visual working memory, which can have a significant negative effect on learning (Squeglia et al., 2012). Interestingly, adolescents undergoing rehabilitation for alcohol dependence show worse performance on verbal and non-verbal memory tasks relative to controls, as well as reduced hippocampal volume (Brown et al., 2000; Tapert and Schweinsburg, 2005). These structural and functional changes are bound to have long-lasting effects.

Tobacco use has been shown to increase the risk of addiction to other substances. Human and animal studies of tobacco use show impairments in learning capacity, memory, attentional control, mood, impulse control, and behavioral problems, even when consumed in small doses (Abreu-Villaça et al., 2003; Counotte et al., 2009; Gould and Leach, 2014; US Department of Health and Human Services, 2016; Valentine and Sofuoglu, 2018;

Zarrindast and Khakpai, 2019; Leslie, 2020). While tobacco use among young people has been a concern for several decades, the relatively recent "new wave" of flavored e-cigarettes has worsened the problem, as these are particularly popular among teenagers (Brown et al., 2000). While flavored e-cigarettes are mostly marketed to people wanting to quit, users are often young people who never smoked before and who mistakenly believe that e-cigarettes are less harmful than conventional cigarettes (Flay et al., 1994; Biederman et al., 2000; Kim et al., 2009). Besides nicotine, e-cigarettes contain substances- some with carcinogenic, pro-inflammatory and immunosuppressive potential- whose short and long-term effects are still unknown (Hill et al., 2005; Mays et al., 2014).

Alcohol and nicotine are thought to be the gateway for illegal drugs like Cannabis (Secades-Villa et al., 2015), which also impairs learning, memory and attention. Most of these effects are dose-dependent, with considerable interindividual variation (D'Souza et al., 2008; Ramaekers et al., 2009; Theunissen et al., 2012; Petker et al., 2019). Chronic marijuana use in adolescents can lead to irreversible IQ loss, even when use is interrupted in adulthood (Meier et al., 2012). Also, Owens et al. (2019) reported that a positive urine screen for THC was associated with lower performance on working memory tasks, as well as reduced fMRI activity in the prefrontal cortex, posterior parietal cortex, supplementary motor area, and insula, even when there was no previous history of cannabis use. Furthermore, since learning consolidation is aided by positive emotions (Tyng et al., 2017) and marijuana is involved in the processing of negative emotions (Bossong et al., 2013), its use may play an additional negative role in learning.

Finally, as mentioned above, one major consequence of substance abuse in school-aged children (besides the cited neurophysiological, social and emotional issues) is an increased school dropout rate (Tice et al., 2017; Valkov, 2018), a critical problem in Brazilian education that is also fueled by inefficient public policies, family disruption, and learning difficulties, among other factors (Vasters and Pillon, 2011; Cardoso and Malbergier, 2014; Bittencourt et al., 2015; de Silva Filho and Araújo, 2017).

NEUROSCIENCE AS AN ALLY TO EDUCATION: A TOOL TO PREVENT USE/ABUSE

Neuroscience knowledge can be used to help kids and teens foster healthy cognitive and emotional skills that will help them make choices regarding drug use and other behaviors. However, it is often challenging to present this knowledge in a way that is accessible and easy to relate to, and one must always consider individuals' prior knowledge and experience (Bruer, 1997; World Health Organization [WHO], 2004; Sigman et al., 2014; Horvath and Donoghue, 2016). The choice of language is critical, as oversimplifications could generate more neuromyths (Howard-Jones and Fenton, 2012). Furthermore, one must also consider the audience's expectations and concerns, their religious and ethical values, and their socio-economic status.

Since most research is published in English, an added challenge for scientists and other professionals in non-English speaking countries is translating scientific findings (as well as adapting them) for a non-English speaking audience (Márquez and Porras, 2020; Roche et al., 2020). A major aim of scientific communication is to reach people who do not work in the areas of science or health and provide them with the opportunity and tools to understand and discuss issues that are of interest to society, such as drug abuse (Fischhoff, 2013). **Figure 1** represents a model of what this process should include, from scientific information adapted by scientists for proper communication to the elaboration/modification of targeted public policies.

In line with this proposal and following UNESCO'S recommendation for educators to apply interactive teaching methods (UNESCO et al., 2017), our group previously developed a neuroscience-based board game called "Crash: find the exit" to promote information, engagement and dialogue at schools about substance abuse and its effects on the central nervous system (Da Silva Chagas et al., 2020). In this collaborative game developed for middle and high school students (ages 12 and older), we present information about 22 neuroactive drugs (e.g., depressants, hallucinogens, stimulants, anabolic steroids, and prescription drugs) as well as brain anatomy, cell types/structures, neurotransmitter actions, the impact of drug abuse on nervous system physiology, and the mechanisms underlying overdose (including effects on other systems, such as cardiovascular and renal). We also added discussion points about depictions of drug use in series or films, making it a particularly interesting experience for young audiences (Da Silva Chagas et al., 2020). Other initiatives for teaching young people about drug abuse have also employed games and even interactive platforms (Miller et al., 2006; Cheng et al., 2011; Klisch et al., 2013; Epstein et al., 2016; Kapitány-Fövény et al., 2018; Stapinski et al., 2018). Such projects have shown positive results in reducing first use, preventing transition to addiction, and overall prevention (Faggiano et al., 2014).

Importantly, interventions are most effective if they are tailored to the group's particular age and risk level (Gilligan et al., 2019). According to MacArthur and colleagues, school programs target normative beliefs (i.e., beliefs held by peers or other important people that influence kids' behaviors), establish a bond with the school, and train risky behavior avoidance. However, this approach does not establish a dialogue or promote adolescents' critical thinking or their ability to make choices. Instead, it aims to impose socially desirable behaviors while avoiding those endorsed by peers (Silva, 2016; MacArthur et al., 2018).

According to Faggiano and colleagues, there are three reasons why schools are the right environment to implement drug-prevention programs: (1) four out of five tobacco smokers start before adulthood, thus substance use prevention should focus on school-age children and adolescents before their beliefs and expectations about substance use are established; (2) schools offer the most systematic and efficient way to reach significant numbers of young people each year, and (3) in most countries, schools can adopt and enforce a wide range of educational policies (Faggiano et al., 2005). While other types of interventions

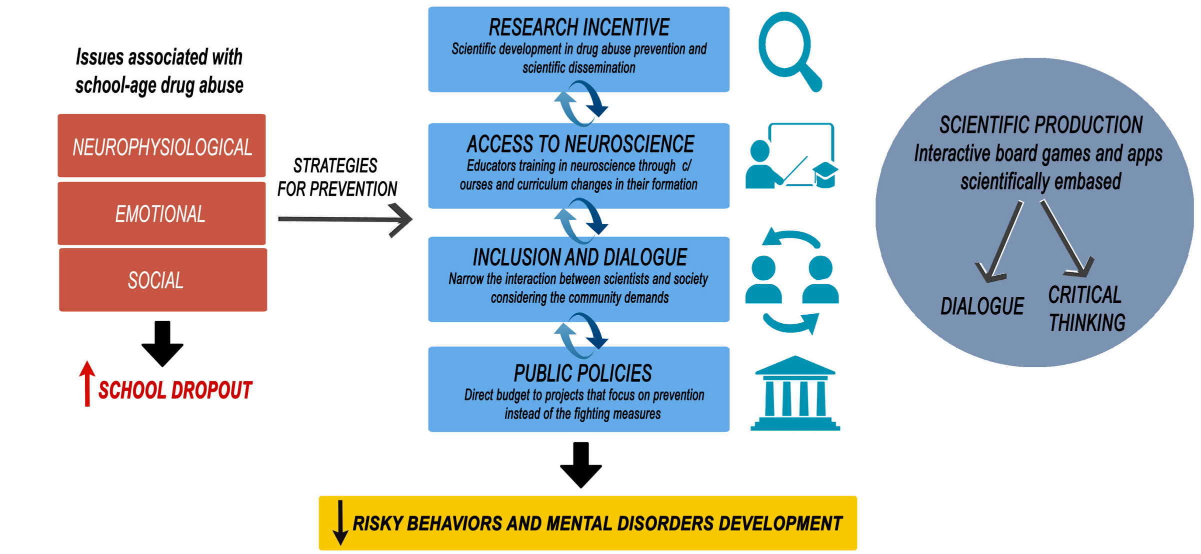

FIGURE 1 | This figure illustrates our view of what a successful educational drug abuse prevention program should include. On the left side, we list the main issues associated with school-age drug abuse, which include neurophysiological, emotional, and social factors that are known to increase rates of school dropout. On the right side of the figure are efforts of scientific production, including interactive games and courses, which generate dialogue and critical thinking and, in turn, promote research incentives, access to neuroscience, inclusion and dialogue, and public policies (middle panel), all of which can help reduce risky behaviors and mental disorders.

have been proposed, including those targeting individuals and families (Carney et al., 2016; MacArthur et al., 2018), evidence indicates that school-based interventions are more effective (Faggiano et al., 2005, 2014; Fletcher et al., 2008; Carney et al., 2016; Lichtenberg et al., 2020).

As discussed by Sigman et al. (2014), among others, social development requires us to build a bridge between neuroscientists and school educators. Scientists develop tools, technologies and educational approaches that engage young people and promote experiences that consolidate learning. School educators, in turn, can use their expertise in dealing with different age groups to disseminate the information in a palatable and efficient manner (Howard-Jones and Fenton, 2012). We advocate in favor of a two-way partnership between researchers and teachers or research centers and schools aiming to find creative alternatives to presenting important information (e.g., about drug abuse[1]). These approaches should be as fun, interactive and engaging as possible (Da Silva Chagas et al., 2020).

Importantly, one should always engage the participation of doctors, therapists and other health workers directly involved in drug abuse treatment, as these professionals can educate the public about the negative impact of drug abuse not only on physical and mental health, but also on individuals' social well-being (e.g., work and relationships). Thus, by sharing their real-life experiences—which are usually not described in scientific articles—health professionals add a fundamental piece to the drug-abuse conversation started by scientists, family members, educational staff, and society. In essence, they can add yet another 'human' component to complement the statistics (Mills and Wonoprabowo, 2020).

Another important strategy is to be welcoming and engaging toward families, as several studies have reported an association between child/adolescent substance use/abuse and their parents' own history of substance and/or psychiatric disorders, two variables included in the list of family-based Adverse Childhood Experiences (ACEs) (Forster et al., 2018; Shek et al., 2020).

PUBLIC POLICIES: COMBATIVE vs. PREVENTIVE STRATEGIES

In 2018, an estimated 269 million people worldwide had used drugs at least once (UNODC, 2021). In Brazil, among 50,890 interviewed public and private elementary and high school students from all 27 Brazilian capitals, this number was 13,000, or 25.5% (see text footnote 1). These high numbers may be attributed to inefficient policies implemented in Brazil, which, as mentioned before, favor a combative and prohibitive approach, rather than one centered on education and prevention (VI LENADE, 2010). In 2017, one billion reais (approximately 186 million US dollars as of August 2021) were invested in anti-drug laws by the state of Rio de Janeiro. This amount would be enough to fund the education of 252,000 high school students or 32,000 public university students for an entire year or build 121 schools for more than 77 thousand new high school students

[1] According to data from the sixth national survey on psychotropic drug use among public and private elementary and high school students.

(Lemgruber et al., 2021). These data suggest that money allocated to "fight drugs" (i.e., costs associated with public safety, public ministry and defense, the rehabilitation of juvenile offenders, and the prison system) might be better used in preventive programs. Scientists and educators should join forces to develop programs that follow this line of thinking and that meet the needs of communities from different socioeconomic levels and cultures in different parts of the world.

However, not all prevention-based programs are successful. In the US, two well-known campaigns–"Just Say No" and its byproduct DARE (Drug Abuse Resistance Education)–were developed in the early 80s and were implemented for many decades. Despite extraordinary government investments and insistence on these programs, it is generally known that they failed at what they proposed to do (Pan and Bai, 2009; Lilienfeld and Arkowitz, 2014). While the approach was preventive and not combative, the "Just Say No" campaign did not provide any useful information or tools for young people to make the right decisions autonomously. While the DARE campaign[2,3] did involve some drug-related education, its approach was never inclusive or interactive. The same failure has been observed with a Brazilian adaptation of these programs, a project called PROERD (Educational Program for Drug Resistance and Violence) (Sanchez et al., 2021), which has traditionally followed a more combative approach. In sum, none of these programs invite young people to think, judge, evaluate or make their own decisions.

On the other hand, positive results have been observed with the application of some non-normative programs in Europe. A study conducted simultaneously in Austria, Belgium, Germany, Greece, Italy, Spain, and Sweden aimed to prevent/avoid the use (experimental and regular) of alcohol, tobacco, and illicit drugs among students 12–14. In this 1 h/week in-school intervention over 12 weeks (with an 18-month follow-up), students learn about different substances and search for the associated toxic properties and physiological alterations. This study resulted in a reduction of about 38% for alcohol use and 26% for cannabis use (Faggiano et al., 2010). Moreover, other reviews covering 29 and 51 US-based studies, respectively (Faggiano et al., 2005, 2014) indicate that school-based programs produce a Number Needed to Treat (NNT) ratio of 33 for marijuana use (i.e., one out of every 33 students will be positively influenced by the intervention and will choose not to smoke marijuana), which is considered successful compared to similar studies.

More recently, programs like those cited above have been gradually implemented in school curricula in some countries. In the US, the "Safety first Program" includes 15 45–50 min classes containing teacher-guided interactive activities providing information regarding substances, their effects and drugs policies. This program is part of Drug Policy Alliance (see text footnote 2), a US-based policy that trains high school teachers to converse openly with their students to help them make better drug-related choices. In Australia (see text footnote 2) a similar initiative is implemented from the beginning of the educational process as part of the "health and physical education" curriculum. The goal is to promote a discussion about drugs and their impact on different levels, including personal, familial and community. This Australian Program revisits the school curriculum early on (foundation to year 10), providing young people with honest and scientifically accurate information that is age-appropriate and thus enables them to evaluate information critically and consciously. Following educational public policies, successful programs cover topics such as HIV transmissibility (needle sharing), teenage pregnancy (considering the impact of drugs in fetal development), chemical dependence, mental health disorders, and the consequences of car accidents (e.g., resulting from drunkenness), all potential consequences of drug use/abuse (UNODC, 2021).

CONCLUSION

While, there is some disagreement on the potential contribution of using neuroscience-based knowledge in the classroom (and how such contributions should be implemented) (Bruer, 1997; Sigman et al., 2014; Horvath and Donoghue, 2016), we strongly believe there is an effective way of using scientific knowledge in favor of social development, as has been shown with several successful projects cited above. However, it is important to emphasize that such efforts should engage teachers, parents and the community at large to (1) create a positive atmosphere that promotes open discussion; (2) avoid spreading erroneous or misleading information about drug abuse or other neuroscience concepts; (3) improve and stimulate neuroscience knowledge as a tool to prevent drug use/abuse among the youngest; (4) guide teachers and students on how to approach this topic creatively; (5) legitimize the school's role in transforming society while providing knowledge to both children/adolescents and their communities; (6) stimulate the study/popularization of neuroscience in schools by leading important discussions about social development; (7) promote the dissemination of this content beyond the school environment to promote critical reflection in the community at large.

In this paper, we show how strategies that aim to fight drug use by instilling fear or teaching young people to avoid certain behaviors often meet little or no success, while those that foster inclusion and incite dialogue and understanding are much more effective. Conducting fun activities while teaching neuroscience in an audience-appropriate language can be an excellent tool in such efforts. In Brazil, efforts to establish a bridge between the (neuroscience) laboratory and schools as well as the community at large have been increasing in the last few years. For such efforts to work, scientists must find a way to work side by side with people in the schools (teachers, students, families, staff), listening to their needs and finding new ways to provide information through neuroscience-based activities. The development of socially innovative tools such as the board game developed by our group pave the way for new similar approaches.

[2]Drug Policy and Alliance (2021). https://drugpolicy.org/resource/safety-first-real-drug-education-teens

[3]Australian curriculum review (2021). https://www.australiancurriculum.edu.au/f-10-curriculum/health-and-physical-education/structure/

In addition, the discussion about issues like drug abuse needs to be encouraged at home as well. The first critical step is to start the dialogue by making information accessible and motivating scientists to engage society. These scientists can then join forces to develop new preventive strategies. For now, our aim is to expose these ideas and encourage scientists, educators and policymakers around the world to actively engage in such efforts and thus contribute to improving society's knowledge and well-being.

DATA AVAILABILITY STATEMENT

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding author.

AUTHOR CONTRIBUTIONS

TM, AA, and PO-S designed the study. TM, LS, HS, and PO-S managed literature searches and wrote the manuscript. EG-d-A, AA, and PO-S critically reviewed the manuscript. LS, HS, and PO-S designed the figure. All authors contributed to and approved the final manuscript.

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