Research Topics

Enhanced learning and teaching via neuroscience

Edited by
Lorna Uden, Gregory Siy Ching and
Amy Corrinne Roberts

Published in
Frontiers in Psychology
Frontiers in Education

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ISSN 1664-8714
ISBN 978-2-8325-3921-7
DOI 10.3389/978-2-8325-3921-7

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Enhanced learning and teaching via neuroscience

Topic editors
Lorna Uden — Staffordshire University, United Kingdom
Gregory Siy Ching — National Chengchi University, Taiwan
Amy Corrinne Roberts — University of Wyoming, United States

Citation
Uden, L., Ching, G. S., Roberts, A. C., eds. (2023). *Enhanced learning and teaching via neuroscience*. Lausanne: Frontiers Media SA. doi: 10.3389/978-2-8325-3921-7

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frontiers | Frontiers in Psychology

TYPE Editorial
PUBLISHED 31 October 2023
DOI 10.3389/fpsyg.2023.1305618

Check for updates

OPEN ACCESS

EDITED AND REVIEWED BY
Douglas F. Kauffman,
Medical University of the Americas – Nevis, United States

*CORRESPONDENCE
Gregory Siy Ching
gregory_ching@yahoo.com;
gching@nccu.edu.tw

RECEIVED 02 October 2023
ACCEPTED 20 October 2023
PUBLISHED 31 October 2023

CITATION
Uden L and Ching GS (2023) Editorial: Enhanced learning and teaching via neuroscience. *Front. Psychol.* 14:1305618. doi: 10.3389/fpsyg.2023.1305618

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Editorial: Enhanced learning and teaching via neuroscience

Lorna Uden[1] and Gregory Siy Ching[2]*

[1]School of Computing, Staffordshire University, Stoke-on-Trent, United Kingdom, [2]Graduate Institute of Educational Administration and Policy, National Chengchi University, Taipei, Taiwan

KEYWORDS

neuroscience, educational neuroscience, brain and learning, pedagogy, teaching and learning process

Editorial on the Research Topic
Enhanced learning and teaching via neuroscience

Human development and learning are fundamentally influenced by neural mechanisms, which are studied in neuroscience. The purpose of educational neuroscience is to translate research findings from neuroscience into educational practice and policy by understanding how education affects the brain. The goal of this emerging field is to link basic neuroscience, psychology, and cognitive science research with educational technology. In this Research Topic, nine articles are published. The first paper is Fang et al.. This opinion article discusses asymmetrical transfer as a reflection of functional lateralization in the left and right hemispheres of the brain. By utilizing this interlimb phenomenon, it may be possible to enhance the efficiency of time spent teaching and learning as a novel sport skill. The second paper is, Gholami et al.. This paper presents an empirical model of teachers' neuroplasticity knowledge, mindset, and epistemological beliefs. The study found that teachers with a higher score in the knowledge of neuroplasticity were more likely to have a growth mindset and a more sophisticated epistemological belief system. As a result of their knowledge of neuroplasticity, teachers' epistemological belief systems were also indirectly affected by their mindsets.

The third paper is, Meyerhofer-Parra and González-Martínez. It is a review of transmedia storytelling, which is found to promote learning engagement, but scaffolding is still needed to consolidate learning. Moreover, to guarantee a true participatory culture requires the integration of more elements that incorporate accessibility into didactic strategies, providing opportunities for learning across different styles.

The fourth paper is Uden et al.. Based on concepts from neuroscience, this paper presents an Integrated Science, Technology, Engineering, and Mathematics Projects Based Learning (STEM-PjBL) method for teaching physics to secondary students. The study found that the method facilitates the development of a commitment to physics as well as an interest in learning the subject in general. A key component of the guidelines is the idea to provide students with opportunities to practice the skills of problem-solving, critical thinking, and collaboration.

The fifth paper is Novak-Geiger. This paper is a study of neuromyths. It has been found that pedagogical psychology and neuroscience training can encourage the development of the ability of a student to recognize true and false statements in a variety of situations. By using intervention approaches that focus on a combination of activating rational thinking as well as non-prescriptive approaches, such as teacher professional development workshops and seminars focusing on the neuroscience of learning, it is possible to dispel beliefs in neuromyths and to establish evidence-based teaching practices in the classroom.

The sixth paper is Lu et al.. As the paper describes, neural markers are closely associated with attitudes toward foreign languages and the ways in which they contribute to performance in foreign languages. Based on the results of the study, it was found that subjective attitudes toward academic challenges have objective neural signatures and can have a significant effect on an individual's brain activity when in a task-like environment. The simple explanation for this is that there seems to be a domain-specific nature to the neural signatures of academic attitudes as opposed to those of general attitudes. As such, it is important to consider domain-specific factors when studying academic attitudes.

The seventh paper is Frei-Landau et al., the paper presents a project using digitally-delivered educational neuroscience in teacher education is examined, with the aim of gaining an understanding of the learning outcomes of such a platform in order to increase the quality of teacher education. As a result of employing a qualitative approach, the study identified four underlying learning outcomes: a better understanding of the brain-based mechanisms of neurodevelopmental disorders, enhanced empathy, a better understanding of the teachers' professional role, and pedagogical adaptations that were designed. It is important to note that this study provides a theoretical insight into some of the ways in which digitally delivered educational neuroscience serves as a tool for promoting inclusion in society.

The eighth and nineth papers are theoretical articles: Tokuhama-Espinosa and Borja and Tokuhama-Espinosa et al.. Using neuroconstructivism and the hierarchy of learning trajectories as a starting point, the eighth paper reexamines these theories and combines them with psychology and the way human beings interact during the teaching-learning process to suggest that radical neuroconstructivism be viewed as the framework by which teachers' professional development should take place. Using the radical neuroconstructivism framework, teachers may be able to make more visible the content knowledge that they acquire as part of their ongoing professional development program. The last paper proposes that explicit instruction of "mental frameworks" may help organize and formalize the instruction of thinking skills that underpin problem-solving—and by extension–that the more such models a person learns, the more tools they will have for future complex problem-solving.

In summary, the papers in this Research Topic highlight the emerging field of educational neuroscience for teaching and learning. These papers emphasize that using research from neuroscience, psychology, and cognitive science, can provides more effective teaching methods and techniques that can be used in a wide variety of educational settings to improve learning by students.

Author contributions

LU: Conceptualization, Data curation, Formal analysis, Project administration, Supervision, Validation, Writing—original draft, Writing—review & editing. GC: Conceptualization, Data curation, Formal analysis, Supervision, Validation, Visualization, Writing—original draft, Writing—review & editing.

Funding

The author(s) declare that no financial support was received for the research, authorship, and/or publication of this article.

Acknowledgments

Thanks to all the authors who contributed to this Research Topic of *Enhanced learning and teaching via neuroscience*.

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TYPE Opinion
PUBLISHED 07 November 2022
DOI 10.3389/fpsyg.2022.1029888

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OPEN ACCESS

EDITED BY
Gregory Siy Ching,
Fu Jen Catholic University, Taiwan

REVIEWED BY
Selcuk Akpinar,
Nevşehir Haci Bektaş Veli University, Turkey
Sheilla Trajera,
University of St. La Salle, Philippines

*CORRESPONDENCE
Qun Fang
2020910112@qdu.edu.cn

SPECIALTY SECTION
This article was submitted to Educational Psychology, a section of the journal Frontiers in Psychology

RECEIVED 28 August 2022
ACCEPTED 24 October 2022
PUBLISHED 07 November 2022

CITATION
Fang Q, Xia Y, Zhang X and Huang F (2022) Asymmetry of interlimb transfer: Pedagogical innovations in physical education. *Front. Psychol.* 13:1029888.
doi: 10.3389/fpsyg.2022.1029888

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Asymmetry of interlimb transfer: Pedagogical innovations in physical education

Qun Fang*, Yuhang Xia, Xiaochao Zhang and Fang Huang

School of Physical Education, Qingdao University, Qingdao, China

KEYWORDS

interlimb transfer, asymmetry, hemispheric lateralization, physical education, pedagogical innovation

Introduction

Interlimb transfer has long been identified in motor learning, with the consensus that the first research can be traced back to 1894 (Scripture et al., 1894). Effects of unilateral practice transfer to the contralateral limb, resulting in skill improvement of the untrained side (Green and Gabriel, 2018). Research evidence based on the neuroimaging technique suggests that interlimb transfer is more than a phenomenon at the behavioral level. In fact, it is associated with strengthened neural correlates within the motor network (Dirren et al., 2021). A noticeable feature of interlimb transfer is the asymmetrical pattern which indicates greater transfer in one direction than that in the other (Wang and Sainburg, 2004, 2006). Asymmetry of interlimb transfer has been well-documented in a number of motor learning research on manual performance (Sainburg and Wang, 2002; Lavrysen et al., 2003; Teixeira and Caminha, 2003; Galea et al., 2007). The typical design induces learning experience during the experiment by means of visuomotor rotations (Wang and Sainburg, 2004, 2006). Participants initially performed an aiming task by moving a cursor from a start point to a target over a tablet. The cursor displayed the location of the finger directing the cursor. After practices under normal circumstances, visual perturbations were assigned by 30° counterclockwise rotation. In the visuomotor rotation experiment, motor learning represents conscious and progressive corrections for perceived movement errors due to the distorted visual feedback (Taylor et al., 2014).

Theories on the asymmetrical interlimb transfer have been developing over the past decades. The proficiency model is an early hypothesis to provide insights into the asymmetrical transfer. Dominant hemisphere/hand is more proficient than non-dominant hemisphere/hand in motor learning. Practice on the dominant side results in more motor information available for transfer to the non-dominant side. Therefore, the model suggests greater transfer to the non-dominant limb performance following the dominant limb practice (Laszlo et al., 1970). On the other hand, the callosal access model predicts an opposite transfer direction which favors the dominant limb performance (Taylor and Heilman, 1980). According to this model, motor information is stored in the dominant hemisphere, thus facilitating learning and performance of the dominant limb due to the direct access to the stored information. While interpreting the asymmetrical transfer to some extent, the two models still show major limitations as each model only covers one direction of interlimb transfer. Based on critical analysis of the limitations, Parlow and Kinsbourne (1989) proposed cross activation model with a particular emphasis on bilateral adaptations. This model is based on the observation that unilateral movement activates both contralateral and ipsilateral motor cortices (Dai et al., 2001; van Duinen et al., 2008). Unilateral training over time leads to neural adaptations in both hemispheres, and the neural adaptations in the untrained hemisphere enhance performance of the untrained limb (Ruddy and Carson, 2013).

The limitations of previous models called for more inclusive perspectives on the asymmetrical transfer in motor learning. Sainburg and Wang (2002) provided evidence that transfer direction was specific to task features. In the same arm reaching task, opposite transfer directions were observed in different kinematic measures. Greater contralateral transfer was identified in the initial direction of right arm movements under the rotated visual conditions. On the other hand, right arm training resulted in greater improvement in the final position accuracy of left arm movements. The findings suggest complex mechanisms underlying interlimb transfer, leading to further investigations on the functional specialization in left and right hemispheres.

Dynamic-dominance hypothesis assumes distinct neural mechanisms for particular movement features (Bagesteiro and Sainburg, 2002). While the dominant system is responsible for the regulation of dynamic characteristics of movement (i.e., control of trajectories and force production), the non-dominant system processes visual-spatial information of movement (i.e., control of final positions and targeted precision) (Sainburg, 2002; Stöckel and Weigelt, 2012). Hemispheric specialization for different motor control mechanisms has been shown to influence directions and magnitude of interlimb transfer (Sainburg et al., 2016). With the increasing understandings of hemispheric lateralization and interlimb transfer, the model of specialized processing and transfer was proposed with an essential hypothesis that practice involving the specialized hemisphere-effector system induces a larger transfer of learning than the non-specialized, less efficient hemisphere-effector system (Stöckel et al., 2011). Recent research provided evidence for the model of specialized processing and transfer. In a grooved pegboard task, right-handed participants showed greater transfer after right hand practice than that after left hand practice whereas left-handed participants performed the task with comparable magnitude of transfer after practice on each hand (Wang et al., 2020). Handedness is reflective of hemispheric asymmetry. The different transfer directions between right- and left-handed individuals suggest the impact of hemispheric asymmetry on interlimb transfer. Additionally, hemispheric activations tend to become less asymmetrical in response to increased task complexity. Asymmetrical transfer has been reported in simple tasks during which hemispheric activation is lateralized. On the other hand, complex tasks stimulate bilateral activations, leading to symmetrical interlimb transfer associated with the reduced hemispheric lateralization (Wang et al., 2022). Therefore, the findings of handedness and task complexity suggest that the model of specialized processing and transfer can provide valid interpretations on asymmetry of interlimb transfer during motor learning.

Motor learning research has been conducted to expand understandings of the neural mechanisms. However, existing research with the purpose of applying neuroscience knowledge and principles to enhance motor learning is still limited. An interesting speculation can be reached about the feasibility to enhance teaching and learning in physical education (PE) by taking advantage of the asymmetrical phenomenon in interlimb transfer. So far, interlimb transfer has been mainly investigated by simple motor actions such as finger tapping and pegboard tasks. It is reasonable to examine whether the asymmetrical pattern observed in the laboratory settings can be extended to the practical conditions in PE classes. The current study proposed the opinion that asymmetry of interlimb transfer may contribute to pedagogical innovations in PE by facilitating the process of teaching and learning sport skills. PE class is the primary affordance for students to learn a novel sport skill (Stöckel et al., 2011). Research on asymmetrical interlimb transfer implies practical value in developing effective teaching strategies to enhance sport skill acquisition.

Pedagogical innovations in PE

Asymmetry of interlimb transfer is indicative of hemispheric functioning. Neuroimaging evidence has shown adaptations in neural circuits associated with improved performance of the untrained limb after unilateral training (Oosawa et al., 2019). Childhood and adolescence are critical periods during which the nervous system is highly plastic (Shaw et al., 2006; Ismail et al., 2017). PE class design in consideration of neural functioning may enhance sport skill acquisition. In recent years, neuroscience is characterized by prominent progress in improving the teaching and learning process for many subjects (Baena-Extremera et al., 2021). Research on asymmetrical interlimb transfer may provide a promising approach to integrate neuroscience into class design and organization, leading to pedagogical innovations in the field of PE.

Class design based on asymmetrical interlimb transfer

While improved performance of the trained limb indicates the principle of specificity, it is also necessary to notice the transfer effects which enhance performance of the untrained limb. Because interlimb transfer is asymmetrical in direction and magnitude, PE teachers and practitioners should consider practicing the side that results in larger transfer effects. For a specific sport skill, if the right limb practice benefits both right and left limb performance whereas the left limb practice only produces positive effect on the left limb performance, a reasonable selection is to practice the skill with emphasis on the right side. Haaland and Hoff (2003) designed a soccer training program in which the experimental group performed skill practice by non-dominant (left) foot and the control group practiced with no particular demand on which side to use. The experimental group enhanced both left and right foot performance, whereas the control group only improved right foot performance. Between-group comparisons indicated that practice on the non-dominant foot resulted in superior left foot performance and comparable right foot performance to the control group. The findings warrant implementing non-dominant foot practice in acquisition of basic soccer skills.

Whether dominant or non-dominant limb practice produces greater transfer depends on the inherent motor components of the task (Sainburg and Wang, 2002). For the skills involving the visual-spatial information which specializes in the right hemisphere/left limb, particular emphasis on the left limb should be given during the practice. Additionally, dynamic characteristics of movement are processed in the left hemisphere/right limb system. Greater transfer effects can be achieved by the right limb practice on the skills involving the regulation of movement dynamics.

Evidence in accordance with the hypothesis was provided in a study which examined two types of throwing skills with particular demands on accuracy and force production (Stöckel and Weigelt, 2012). The training program lasted 8 weeks during which participants began the training with one hand in the first 4 weeks and then switched to the other hand practice in the last 4 weeks. In the task with an emphasis on throwing accuracy, initial practice on the non-dominant hand enhanced performance of both hands to a greater extent than the opposite order. In contrast, participants with initial practice on the dominant arm showed larger beneficial transfer than their counterparts with initial practice on the non-dominant arm when performing the throwing task with an emphasis on maximum force.

The throwing tasks with a particular demand on accuracy involves visual-spatial processing (e.g., trajectory control) in the right hemisphere/left limb system. Practice on the left hand is in line with the specialized hemisphere-effector system, thus resulting in greater transfer effects. Same rules can be applied to the task with a demand on throwing force. The left hemisphere/right hand system specializes in regulation of movement dynamics such as force production (Serrien et al., 2006). Practice on the dominant hand establishes a better representation of the specialized left hemisphere/right hand system in motor skill acquisition, leading to larger transfer from the right hand practice to the left hand performance.

Additional evidence was provided by 6-week fencing training sessions which were developed in accordance with the hemispheric lateralization hypothesis (Witkowski et al., 2018, 2020). The ratio of non-dominant (left) side to dominant (right) side practice was 3:1, as each drill repeated three times on the left limb associated with one practice on the right limb. The control group, on the other hand, implemented practice only with the dominant side. Although fencing is a unilateral sport, bilateral practice resulted in greater improvement in hitting accuracy of the dominant hand than that after unilateral practice. Because the right hemisphere/left limb system specializes in spatial characteristics of movement, training with an emphasis on the left side enhances the specific neural network, producing transfer effects to the dominant hand performance. Therefore, evidence from the existing research implies promising applications of asymmetrical transfer to PE. Class design in accordance with asymmetry of interlimb transfer would promote time efficiency of teaching and learning.

Framework for future endeavors

Despite the promising applications of interlimb transfer, direct evidence with respect to pedagogical practice is still limited, which warrants future research on the relevant topic. A four-phase framework to guide subsequent research work is provided in this section.

Successful application of asymmetrical interlimb transfer to PE underlies the link between the trained limb and the specialized hemisphere-effector system in skill learning. The initial phase should classify individual sport skills (e.g., passing and dribbling) into corresponding hemisphere-effector systems. The fundamental work is to identify the skills which are dominantly processed by the right hemisphere/left limb system and those mainly processed by the left hemisphere/right limb system. The second phase involves conducting experimental studies to testify efficacy of the existing models in predicting and explaining the effects of applying asymmetrical transfer to sport skill acquisition. Marinsek (2016) provided a valid study design to examine lateral asymmetry in dribbling skill practice. Participants were randomly allocated to dominant limb practice group, non-dominant limb practice group, or bilateral practice group. Outcomes in relation to each teaching strategy were examined by within- and between-group comparisons. The third phase, after the study design and implementation, aims to interpret the results by available theoretical models. The findings may be inconsistent with the hypothesis that practice on the specialized hemisphere-effector system induces a better transfer of learning across limbs. Indeed, inconsistent findings have been reported by the existing literature. For the dribbling practice in soccer, some studies identified better learning outcomes associated with non-dominant limb practice (Haaland and Hoff, 2003; Teixeira et al., 2003), while evidence also indicated favorable transfer effects after dominant limb practice (Marinsek, 2016). The magnitude and direction of transfer may be influenced by various factors such as age of participants (Marinsek, 2016) and types of sport skills (Stöckel and Weigelt, 2012). It is possible that the existing models may be inadequate to interpret all research findings, thus leading to the fourth phase of refining the models if necessary. With the cumulative understandings of the mechanisms underlying interlimb transfer in sport skill acquisition, principles of neuroscience and motor control can be better applied to enhance teaching and learning effects in PE classes.

Conclusion

The current study highlighted asymmetry of interlimb transfer as a potential contribution to pedagogical innovations in the field of PE. Asymmetrical transfer is considered a reflection of functional lateralization in left and right hemispheres. Taking advantage of this interlimb phenomenon may enhance time efficiency of teaching and learning a novel sport skill. The basic rule to guide teaching practice can be summarized in the statement that practice involving the specialized hemisphere-effector system induces greater transfer effects, thus facilitating acquisition of sport skills. The empirical evidence implies high practical value for PE class design and implementation, which warrants future research work on the relevant topic. Accordingly, a four-phase framework was proposed to guide following research and pedagogical practice. The current study calls for more attention to the innovative teaching strategy which indicates a promising combination between neuroscience and PE.

Author contributions

QF and YX prepared the draft. XZ and FH worked on revision and approved the submitted version. All authors collaborated in preparing the manuscript. All authors contributed to the article and approved the submitted version.

Acknowledgments

The authors appreciate the practical insights provided by physical education teachers, Xiaodong Luo from Xiliu Rd. Elementary School, Zibo, China, and Zhe Wang from Qingdao Middle School, Qingdao, China.

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frontiers | Frontiers in Psychology

TYPE Original Research
PUBLISHED 08 December 2022
DOI 10.3389/fpsyg.2022.1042891

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OPEN ACCESS

EDITED BY
Gregory Siy Ching,
Fu Jen Catholic University, Taiwan

REVIEWED BY
Hui-Min Lai,
National Taichung University of Science and Technology, Taiwan
Din-yuang Huang,
Fu Jen Catholic University, Taiwan

*CORRESPONDENCE
Khalil Gholami
khalil.gholami@gmail.com

SPECIALTY SECTION
This article was submitted to Educational Psychology, a section of the journal Frontiers in Psychology

RECEIVED 13 September 2022
ACCEPTED 07 November 2022
PUBLISHED 08 December 2022

CITATION
Gholami K, Alikhani M and Tirri K (2022) Empirical model of teachers' neuroplasticity knowledge, mindset, and epistemological belief system. *Front. Psychol.* 13:1042891.
doi: 10.3389/fpsyg.2022.1042891

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Empirical model of teachers' neuroplasticity knowledge, mindset, and epistemological belief system

Khalil Gholami[1,2]*, Maryam Alikhani[1] and Kirsi Tirri[2]

[1]Department of Education, Faculty of Humanities and Social Sciences, University of Kurdistan, Sanandaj, Iran, [2]Department of Education, Faculty of Educational Sciences, University of Helsinki, Helsinki, Finland

Educational research has shown that teachers' knowledge and beliefs are two important variables that significantly affect their pedagogical practice and decisions. Relying on the premise that knowledge is superior to beliefs in a pure epistemic dimension and rooted in the previous empirical studies, we examined the hypothesis that teachers' knowledge of neuroplasticity affects their epistemological belief system mediated by mindset. Using a survey consisting of established scales about these variables, we collected data from a sample of 345 teachers. Structural equation modeling was performed to test the hypothesis. Results showed that the path coefficients (direct effects) from teachers' knowledge of neuroplasticity to their mindset and epistemological belief system were statistically significant. In other words, we found that teachers with a higher score in the knowledge of neuroplasticity had a growth mindset and a sophisticated epistemological belief system. Teachers' knowledge of neuroplasticity also had an indirect effect on their epistemological belief system mediated by mindset. This result has a conceptual contribution to the literature because it suggests that teachers' knowledge of neuroplasticity is a predicting variable for mindset and epistemological belief system. In practice, it provides us with a tool for developing teachers' growth mindset and sophisticated epistemological beliefs.

KEYWORDS

neuroplasticity, teachers' mindset, epistemological belief system, teachers' knowledge, neuromyths, educational neuroscience

Introduction

This paper is based on the premise that teachers' knowledge of educational neuroscience dispels their naïve epistemological belief systems and fixed implicit theories on intelligence. Many teachers have acquired what Bruner (1996, p. 46) calls "folk pedagogy," which reflects certain "wired-in human tendencies" and some deeply fixed beliefs rooted in their social and personal experiences that lack scientific evidence. Empirical research suggests that a significant part of such folk pedagogy is the prevalence of misconceptions about the brain, which are called "neuromyths," among teachers in different countries and various educational settings (Howard-Jones, 2014; Gleichgerrcht et al., 2015; Dündar and Gündüz, 2016; Ferrero et al., 2016; Düvel et al., 2017; Blanchette Sarrasin et al., 2019; Carter et al., 2020; Torrijos-Muelas et al., 2021; Jeyavel et al., 2022). In 2002, the Brain and Learning project of the Organization for Economic Co-operation and Development (OECD) warned that the rapid proliferation of neuromyths among teachers and other professionals is a challenging phenomenon in educational settings (OECD, 2002). In a comparative study among teachers in the United Kingdom and Netherlands, Dekker et al. (2012) found that, on average, teachers believed 49% of the neuromyths. However, research has provided evidence against such neuromyths, such as left vs. right brain people, only 10% of brain use, multiple intelligences, and visual, auditory, and kinesthetic (VAK) learning styles (Torrijos-Muelas et al., 2021).

Holding a personal belief or relying on knowledge to make pedagogical choices is the matter of warrant by which teachers justify their actions. Adapting from Freeman, there could be four types of warrants in teaching: *a priori* warrant that involves resorting to a pedagogical or scientific principle; an institutional warrant is a justification of a pedagogical choice on the grounds of it being recommended or required in a textbook (institutional–curricular); an empirical warrant is the citation of a frequent occurrence in the classroom or the resorting to personal learning experiences; and an evaluative warrant is a justification of a pedagogical choice on the grounds of a personally held view, value or belief (Nardi et al., 2012). In this research, teachers' knowledge of neuroplasticity relies on *a priori* warrant and teachers' beliefs may be supported by empirical and evaluative warrants. Educators and policymakers need to plan for promoting teachers' knowledge of the brain or educational neuroscience to dispel neuromyths among teachers and thus ground their pedagogical beliefs on priori warrant. Dekker and Jolles (2015) state that "learning about the brain and neuropsychological development in adolescents may increase teachers' understanding of typical adolescent behavior such as risk taking…. This may positively influence teachers' patience and optimism, as well as help them to develop an effective professional attitude toward students" (p.1). Other empirical research suggests that teachers' knowledge of educational neuroscience significantly reduces their neuromyth beliefs (Wilcox et al., 2021; Ferreira and Rodríguez, 2022); improves the quality of learning, and promotes equity among learners (Coch, 2018); enhances educators' pedagogical practice and thinking to meet learners' diverse needs (Walker et al., 2019); provides teachers a platform to promote students' motivation and engagement (Dubinsky et al., 2019); and develops teachers' pedagogical practice, enhances stronger relationships between teachers and learners, and increases meaningful learning (Hachem et al., 2022). A significant part of teachers' folk pedagogy and naïve pedagogical beliefs root in the lack of scientific knowledge about relevant phenomena they deal with in the teaching-learning process. In other words, when teachers have no knowledge about something, there is a strong possibility to grasp false beliefs about it. In line with this concern, we examined the empirical relationship between teachers' knowledge of neuroplasticity, teachers' theories of intelligence or mindset, and teachers' epistemological belief system and posed the following research questions:

1. To what extent does teachers' neuroplasticity knowledge affect their epistemological belief system and mindset?
2. To what extent does teachers' mindset affect their epistemological belief system and mediate the relationship between teachers' neuroplasticity knowledge and their epistemological belief systems?

Definition of the main variables

Generally, neuroplasticity "refers to the capacity of neurons and neural networks to change their connections and behavior in response to experience" (Dan, 2019, p. 1). "Plasticity embodies the idea that the strength of the synaptic connections between neurons is dynamic, becoming stronger with the use or weaker with inactivity…synchronous plasticity in the neural pathways producing specific behaviors results in observable learning" (Dubinsky et al., 2013, p. 318). In the educational context, particularly in schools, teachers' neuroplasticity knowledge has important implications for their pedagogical practice and beliefs toward students' learning. As such, neuroplasticity has been one of the main theme of research in educational neurosciences for teachers' professional development programs (Hachem et al., 2022).

Mindset is defined as "implicit theories about the malleability and stability of human characteristics related to ability, intelligence, and talent" (DeLuca et al., 2019, p. 159). According to Dweck (2007), mindset consists of believing that personal characteristics are either entirely malleable (growth mindset) and thus can be developed or entirely fixed and unchangeable (fixed mindset; see Dweck, 1999; Yeager and Dweck, 2020). Students with a fixed mindset "reject opportunities to learn if they might make mistakes, afraid of effort because effort makes them feel dumb and do not recover well from setbacks" (Dweck, 2007, p. 2). By contrast, "students with a growth mindset seek challenges, rebound from failures, and accept feedback for improvement" (DeLuca et al., 2019, p. 159). There has been increasing interest among educational researchers to examine how teachers' and students' mindsets relate to their practice, beliefs, and other important functions.

Rooted in the theory of personal epistemology, Schommer-Aikins (2004) introduced and defined the concept of epistemological belief system as a system of independent beliefs about "(a) the stability of knowledge, ranging from unchanging knowledge to tentative knowledge; (b) the structure of knowledge, ranging from isolated bits and pieces to integrated concepts; (c) the source of knowledge, ranging from omniscient authority to reason and empirical evidence; (d) the speed of learning, ranging from quick or not-at-all to gradual; and (e) the ability to learn, ranging from fixed at birth to improvable" (p.20). In this way, an individual may hold more than one sophisticated or naïve belief system over a continuum considering different dimensions of the epistemological belief system (Schommer, 1990, 1993). For example, a person may have highly sophisticated beliefs about speeds of learning but a naïve belief about the source of knowledge.

Research conceptual framework and hypotheses

In the present research, considering the main variables, we have formulated four hypotheses. Empirical research has suggested that teaching neuroplasticity in an educational setting induces a growth mindset about motivation, goals, effort beliefs, response to failure, and academic enjoyment (Sarrasin et al., 2018). "If teachers know that the underlying brain networks for planning abilities continue to mature during adolescence and that this development is contingent upon experiences, they will understand that they have to provide more guidance to stimulate the development of students' planning abilities" (Dekker and Jolles, 2015, p. 2). In addition, in teaching studies, researchers are interested in teachers' epistemological belief system and the ways they are related to their pedagogical practices and personal characteristics (Sinatra and Kardash, 2004; Jones and Carter, 2006; Bernardo, 2008; Yilmaz-Tuzun and Topcu, 2008; Topcu, 2013; Bahçivan, 2016; Demirbag and Bahcivan, 2022). In general, sophisticated epistemological belief system enable pre–/in-service science teachers to gain more constructivist perspectives on learning and teaching (Demirbag and Bahcivan, 2022). In most previous studies, both teachers' epistemological belief systems and neuroplasticity knowledge were examined as predicting variables for teachers' pedagogical thinking and practice. We argue that teachers' knowledge of neuroplasticity has however a more concrete epistemic position compared to the epistemological belief system and mindset; thus, we used it as the main predicting variable for teachers' epistemological belief system and mindset. As such, two hypotheses examine the direct effect of teachers' knowledge of neuroplasticity on their epistemological belief system and mindset:

> *Hypothesis 1*: Teachers with correct knowledge of neuroplasticity hold less likely a naïve epistemological belief system.
>
> *Hypothesis 2*: Teachers with correct knowledge of neuroplasticity have less likely a fixed mindset.

Considering mindset, the results of several studies have found that mindset has a significant effect on students' characteristics such as academic achievement, motivation, and effort beliefs (Blackwell et al., 2007); entrepreneurial self-efficacy and career development (Burnette et al., 2020); metacognitive skills on math engagement (Wang et al., 2021); IQ and personality mindset beliefs (Orosz et al., 2017); and stereotype threats about their capabilities (Aronson et al., 2002; Good et al., 2003). In general, the results of these studies have found that students "who hold more of a growth mindset are more likely to thrive in the face of difficulty and continue to improve, while those who hold more of a fixed mindset may shy away from challenges or fail to meet their potential" (Yeager and Dweck, 2020, p. 1; see Dweck and Yeager, 2019). Another major tendency in research on mindset focuses on how teachers' mindset is presented in their pedagogical practices and how that can be integrated into teacher education programs (Rissanen et al., 2018a,b, 2019, 2021; DeLuca et al., 2019). The results of these studies suggest that teachers' mindsets "influence their ways of interpreting students' behavior, learning, and achievements, which in turn guide teachers' pedagogical thinking as well as their practices for motivating the students" (Rissanen et al., 2018a, p. 487). Generally, teachers with a growth mindset tend to engage in a more advanced, flexible, and moral practice while teachers with a fixed mindset tend to engage "in prescriptive and closed-ended tasks with less descriptive feedback" (DeLuca et al., 2019, p. 160). Therefore, in the previous research, the mindset has been mainly used as a predicting variable for students' and teachers' characteristics. In this research, we used mindset as a mediating variable that alters the relationship between teachers' knowledge of neuroplasticity and their epistemological belief system. Therefore, two more hypotheses were posed as follows:

> *Hypothesis 3*: Teachers with a growth mindset hold more likely a sophisticated belief system.
>
> *Hypothesis 4*: Teachers' mindset mediates the negative relationship between teachers' knowledge of neuroplasticity and their epistemological belief system.

Considering these research hypotheses and based on the previous studies, we developed and tested the following research conceptual model (Figure 1).

Materials and methods

Participants

A total sample of 345 teachers from Sanandaj, the capital city of the Kurdistan province of Iran, participated in the present research. The total number of teachers in this region was around 3,000, and the sample size was proportional to its population (Krejcie and Morgan, 1970). The participants were in-service subject (35.9%) and pre-service class (64.1%) teachers. The other teachers' demographic data included gender (female = 30.04%; male = 69.6%), age (18–20 years old = 16.5%, 21–35 = 59.7%, 36 and older = 23.8%), and teaching experiences (pre-service teacher = 64.1%, 1–5 years = 8.7%, 6–10 years = 3.8%, 11–20 years = 9.9%, and 21 years and more = 13.6%). We studied the effects of these demographic data to make sure that the empirical relationship between the main variables is reliable (see the results). The participants were from public schools and participated in the study voluntarily.

Procedure

First, official permissions were granted from the selected public schools and teacher education universities (in Iran called

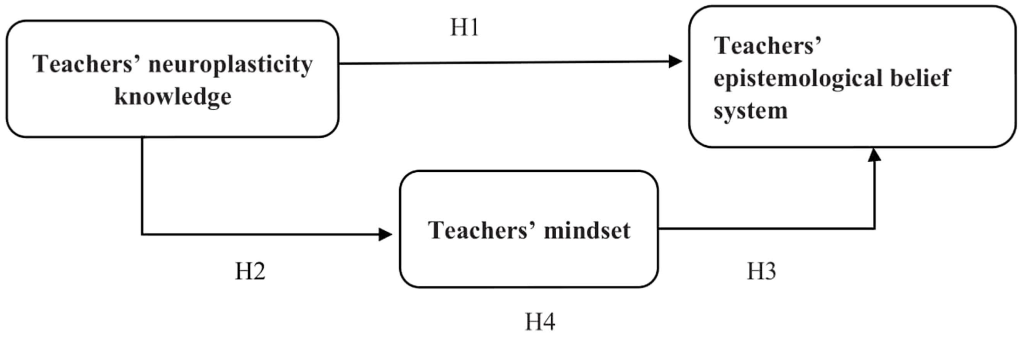

FIGURE 1
The conceptual model of relationships between the main variables of the study.

Farhangian University) to enter the sites for data collection. Second, for in-service teachers, one of the researchers approached the teachers in the selected schools, explained the aim of the research, and asked them to participate in the study voluntarily. For trainee teachers, the researcher and one of the authorities from Farhangian University approached the students while they were in class. Permission from the teacher educators had already been obtained to enter the classes for collecting data. Third, the volunteer teachers were provided a paper questionnaire, and they filled in the questionnaires and returned them to the researchers the same day.

Measures

The survey consisted of four sections. In the first part, participants provided demographic data, including age, gender, years of teaching, and the subject of teaching. The second part consisted of 18 statements about the brain (Dekker et al., 2012). In this paper, we analyzed nine statements that aim at measuring the knowledge of neuroplasticity (Appendix). In the third part, we used six statements from Dweck's scale that measures mindset about intelligence and giftedness (Dweck, 2006). Three statements were about mindset on intelligence, and three statements measured mindset on giftedness. In our previous research, we used this scale, and it had strong construct validity and reliability (Rissanen et al., 2018b; Zhang et al., 2019). The fourth part consisted of 24 statements about the epistemological belief system chosen by Schommer (1998). We used the second-order constructs including four dimensions of the epistemological belief system, namely fixed learning ability, simple knowledge, quick learning, and certain knowledge. Fixed learning ability (items 1–6), statements that measure ability to learn ranging from the belief that the ability to learn is fixed to the belief that it can be improved. Simple knowledge (items 7–13), is statements that measure the structure of knowledge as isolated or highly interrelated pieces. Quick learning (items 14–18), statements that measure the speed of learning, ranging from a belief that learning is quick or all-or-none to a belief that it is gradual. Certain knowledge (items 19–24), is statements that measure the nature of knowledge, ranging from a belief that knowledge is certain to the belief that it is evolving.

For all measures, the answer options were "totally disagree," "disagree," "agree," and "totally agree," which coded 4 for totally agree, 3 for agree, 2 for disagree, and 1 for totally disagree. When entering data in Statistical Package for Social Sciences (SPSS), the following items were reverse-coded: for neuroplasticity, the incorrect items; for mindset, growth items; and for epistemological belief system, sophisticated items. In this way, the higher scores reflect good knowledge, fixed mindset, and naïve beliefs; and the lower scores reflect poor knowledge, growth mindset, and sophisticated beliefs for teachers' knowledge of neuroplasticity, mindset, and epistemological belief system, respectively.

Using confirmatory factor analysis and Cronbach alpha, we examined the construct validity and reliability of the measures. The factor loading of item 1 for mindset and items 6 and 8 for neuroplasticity did not exceed the cutoff value of 0.5 (Hair et al., 2006) and was removed from further analysis (Table 1).

We have reported both absolute (RMSEA) and incremental fit indices (CFI, IFI); (Hu and Bentler, 1999; Hulpia et al., 2009) to examine the validity of the measures. As per Table 1, neuroplasticity showed a good fit considering both types of fit indices. For RMSEA a value <0.08 explains a reasonable model fit (Musek, 2007), and more strictly values <0.06 shows a good model fit (Hu and Bentler, 1999). Considering incremental fit indices, it is generally suggested that a value close to 0.90 or above indicates a good model fit (Hulpia et al., 2009). For mindset and epistemological belief system, CFI and IFI indicated a good fit, however RMSEA for both measures resulted in a poor fit. Lai and Green (2016) proved that such "inconsistency is not diagnostic of particular problems in model specification or data. Instead, it arises because (a) the two indices, by design, evaluate fit from different perspectives; (b) cutoff values are needed and are being (rightly or wrongly) used, and (c) the meaning of "good fit" and how it relates to fit indices are not well understood in the current literature" (p.234). The Cronbach alpha of the three measures was above 0.70, indicating a good reliability (Table 2).

Data analysis

The data were analyzed using AMOS and SPSS version 24.0 for Windows. Hierarchical regression was conducted to examine

TABLE 1 Factor loading for the main variables in the study.

Indicators	Epistemological personal beliefs	Neuroplasticity	Mindset
Fixed learning	0.78		
Simple knowledge	0.77		
Quick learning	0.87		
Certain knowledge	0.64		
(1) Learning occurs through the modification of the brain's neural connections		0.55	
(2) Extended rehearsal of some mental processes can change the shape and structure of some parts of the brain		0.56	
(3) Mental capacity is hereditary and cannot be changed by the environment or experience		0.60	
(4)There are sensitive periods in childhood when it is easier to learn things		0.63	
(5) Learning problems associated with developmental differences in brain function cannot be remediated by education		0.50	
(7) Normal development of the human brain involves the birth and death of brain cells.		0.65	
(9) Vigorous exercise can improve mental function		0.50	
(2) No matter how much intelligence students have, they can always change it quite a bit.			0.62
(3) Students may learn new things, but they cannot change their intelligence.			0.79
(4) Students have a certain talent in certain subjects (e.g., math, sports), and they cannot change it.			0.72
(5) Students can learn new things, but they cannot change their talents.			0.62
(6) If students work hard in any subject, they will be better at it.			0.54

TABLE 2 Construct validity and reliability of the measures.

Variables	Construct validity				Reliability
	CMIN/DF	CFI	IFI	RMESA	α
Neuroplasticity	3.01	0.94	0.94	0.07	0.77
Mindset	5.80	0.939	0.94	0.11	0.79
Epistemological belief system	6.89	0.94	0.94	0.13	0.85

the effects of teachers' neuroplasticity knowledge and mindset (independent variables) on the epistemological belief system (dependent variable) while controlling the effects of age, gender, and years of teaching (background variables). Such an analysis helped us make sure that the claims that explained the structural relationships between independent and dependent variables are epistemologically valid. In social science research, this is called epistemological, ontological, and methodological consistency (Creswell, 2003). Structural equation modeling (SEM) was then performed to examine the effect of teachers' neuroplasticity knowledge (seven indicators or observed variables) on their epistemological belief system (four dimensions) mediating by mindset (five indicators). Therefore, the final model consisted of three latent variables and 16 observed variables. We used SEM because it assesses "the measurement model (how well the measured variables define their respective construct) and structural model (how well the latent constructs relate to each other) simultaneously" (Meyers et al., 2006, p. 637). In the next step, we examined how teachers with sophisticated/naïve beliefs and growth/fixed mindsets were distributed within the status of good/poor knowledge of neuroplasticity. Therefore, all three variables were recoded into two categories, and the cutoff point to divide each scale was 5% trimmed mean. As the results, the cutoff point means were 3.01 for neuroplasticity, 2.33 for mindset, and 2.24 for epistemological beliefs. In other words, teachers with scores below 3.01 were labeled with poor knowledge of neuroplasticity, 2.33 growth mindset, and 2.24 sophisticated beliefs system.

Results

Background variable analysis

Hierarchical regression analysis showed the background variables did not explain a significant variance in teachers' epistemological belief systems [F (3, 341) =0.85, $p = 0.47$, $R^2 = -0.00$]. As per Table 3, in the first step, the background variables entered the model, which accounted for 0.001 variances ($R^2 = 0.001$). The regression coefficients for all background variables were not statistically significant. However, the main independent variables (mindset and neuroplasticity) explained a significant variance in teachers' epistemological belief system [F (3,341) = 92.42, $p < 0.01$, $R^{2adj} = 057$]. The regression coefficients for mindset ($\beta = 0.35$, $p < 0.01$) and neuroplasticity ($\beta = -0.52$, $p < 0.01$) were statistically significant. Table 3 shows the results of the regression analysis.

The results of the regression analysis suggested that background variables of age, gender, and years of teaching had no significant effects on teachers' epistemological beliefs; thus, we proceed to the main analysis to test the main hypothesis promoted in this paper.

TABLE 3 The regression analysis of the background and main variables.

Model	Variables	*R*	R^2	R^{2adj}	*F*	*B*	*β*	*T*	Sig
1	Teaching	0.086	0.007	−0.001	0.85	−0.004	−0.005	0.077	0.938
	Age					0.042	0.052	0.876	0.381
	Gender					0.055	0.063	1.049	0.295
2	Teaching	0.77	0.59	0.59	98.74	0.034	0.041	−0.848	0.397
	Age					0.002	0.002	−0.225	0.822
	Gender					0.028	0.032	1.004	0.316
	Mindset					0.214	0.35	8.69	0.000
	Neuroplasticity					−0.462	−0.52	−12.78	0.000

Dependent variable: teachers' epistemological beliefs.

TABLE 4 The path coefficients of the main variables in the model.

Variable effects in the model	*β* (total effect)	*β* (Direct)	*β* (indirect)	Sig
Neuroplasticity on epistemological belief system	−0.88	−0.72		0.000
Neuroplasticity on mindset	−0.69	−0.69		0.000
Neuroplasticity on epistemological belief system *via* mindset			−0.17	0.000
Mindset on the epistemological belief system	0.24	0.24		0.000

Structural equation modeling

Using SEM, we tested this hypothesis: Teachers with correct knowledge of neuroplasticity have more sophisticated epistemological beliefs, mediating by mindset. Considering the following fit indexes, chi-square test, comparative fit index (CFI), incremental fit index (IFI), and mean square of approximation error (RMSEA), the hypothesized model was evaluated. The results produced acceptable overall goodness of fit index (CMIN/df = 2.91; Hoyle and Isherwood, 2013). In addition, the CFI (0.91), IFI (0.91), and RMSEA (0.07) yielded good indexes (Hu and Bentler, 1999; Musek, 2007; Hulpia et al., 2009). These indexes indicate that the hypothesized model fits the observed data.

Analyzing the regression coefficients, the results showed that the path coefficients (direct effects) from teachers' knowledge of neuroplasticity to their mindset ($\beta = -0.69$, $p < 0.01$) and epistemological belief system on learning ($\beta = -0.72$, $p < 0.01$) were statistically significant. Generally, this means that teachers with a higher score in neuroplasticity have a growth mindset and sophisticated epistemological belief system. In other words, with one standard deviation increase in teachers' knowledge of neuroplasticity, 0.68 and 0.69 standard deviations of their fixed mindset and naïve epistemological belief system decrease, respectively. The path coefficient (direct effect) from mindset to epistemological belief system ($\beta = 0.24$, $p < 0.01$) shows teachers with higher scores in mindset (fixed mindset) are more likely to fall into the category of naïve epistemological beliefs, meaning that with one standard deviation increase in teachers' fixed mindset, their naïve epistemological belief system increase by 0.24 standard deviation.

Teachers' knowledge of neuroplasticity had an indirect effect of −0.17 on their epistemological belief system mediated by mindset. The total effects for all tested paths confirmed the same trend; however, the total effect of the path coefficient from neuroplasticity to the epistemological belief system was larger (−0.88) than the direct effect (−0.72). Table 4 shows the path coefficients of the model.

To evaluate the accuracy of the prediction in the structural equations, we examined the proportion of the variance (R^2) accounted for endogenous variables. The amount of variance accounted for mindset was ($R^2 = 0.47$) and for the epistemological belief system was ($R^2 = 0.81$). These accounted variances are strong enough in educational sciences (Meyers et al., 2006), suggesting a significant contribution to the literature since this model was examined for the first time. Figure 2 shows the final model developed in this research.

Descriptive distribution of variables

As found, teachers' knowledge of neuroplasticity had significant effects on their epistemological belief system and mindset. Descriptive statistics confirmed the same effects. The data analysis showed that 63.4% of teachers with good (correct) knowledge of neuroplasticity were found to have a growth and 36.6% a fixed mindset. In addition, 70% of teachers with good knowledge of neuroplasticity were found to have a sophisticated and 30% a naïve epistemological belief system. The chi-square tests for mindset [χ^2 (df = 1, 21.26) $p < 01$] and epistemological belief system [χ^2 (df = 1, 48.70) $p < 0.01$] showed that these results were statistically significant. Table 5 shows more details about the distribution of the teachers' knowledge of neuroplasticity within their mindset and epistemological belief system.

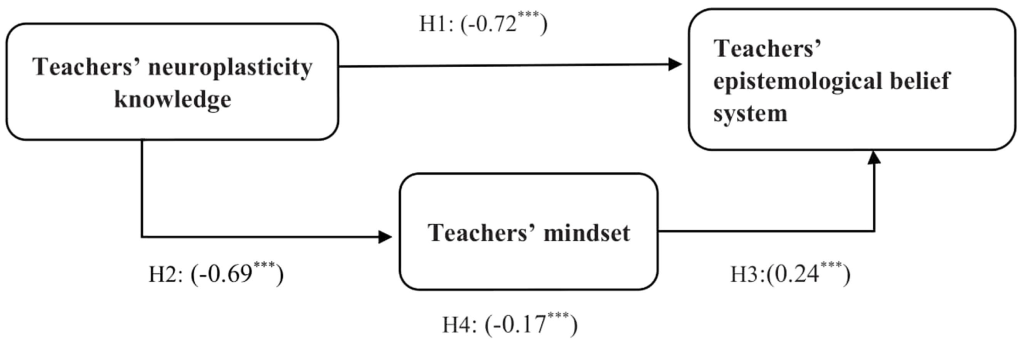

FIGURE 2
The empirical model of teachers' neuroplasticity knowledge, mindset, and epistemological belief system. **significant level.

TABLE 5 Distribution of teachers' mindset and epistemological belief system within the knowledge of neuroplasticity.

Epistemological beliefs		Sophisticated beliefs	Naïve beliefs	Total within neuroplasticity
Knowledge of	Poor	48	103	151
neuroplasticity	knowledge	31.8%	68.2%	43.8%
	Good	135	59	194
	knowledge	70%	30%	56.2%
Total within the		183	162	345
epistemological belief system		53%	47%	100.0%
Mindset		**Growth mindset**	**Fixed mindset**	
Knowledge of	Poor	58	93	156
neuroplasticity	knowledge	38.4%	61.6%	43.8%
	Good	123	71	194
	knowledge	63.4%	37.6%	56.2%
Total within mindset		181	164	345
		52.5%	47.5%	100%

Discussion

Rooted in the existing literature, we posed four hypotheses to examine the structural relationships among teachers' knowledge of neuroplasticity, their epistemological belief system, and their mindset. H1 and H2 examined the direct effects of teachers' knowledge of neuroplasticity on their epistemological beliefs system and mindset. With H1, we stated that teachers' knowledge of neuroplasticity reduces their naïve epistemological beliefs and with H2, we supposed that teachers' knowledge of neuroplasticity decreases fixed mindset. The results showed that both hypotheses were supported by our statistical analysis. All fit indexes suggested that the model was empirically acceptable, thus fitting the observed data. The path coefficients from teachers' knowledge of neuroplasticity to their epistemological belief system ($\beta = -0.72$, $p < 0.01$) and mindset ($\beta = -0.69$, $p < 0.01$) were statistically significant and practically strong. This proved that teachers with correct knowledge of neuroplasticity fall less likely into the categories of a naïve epistemological belief system and a fixed mindset. The existing literature also supports this finding. The results of other studies support that teachers with genuine or scientific knowledge, particularly knowledge about the brain or educational neuroscience, are less likely to have a poor belief system and neuromyths (Dubinsky et al., 2013; Ferrero et al., 2016; Wilcox et al., 2021; Ferreira and Rodríguez, 2022). Teachers' fixed mindset, naïve epistemological beliefs, and neuromyths all constitute a teacher poor belief system that may hinder the quality of their pedagogical skills and decisions.

H3 and H4 were formulated to examine the effects of teachers' mindset on their epistemological belief system. With H3, we tested the direct effect of teachers' mindset stating that teachers with a growth mindset have less likely a naïve epistemological belief system. Through H4, we posed that teachers' mindset mediates the negative relationship between knowledge of neuroplasticity and the epistemological belief system. The results of the data analysis significantly supported both hypotheses. The path coefficient (direct effect) from mindset to epistemological belief system ($\beta = 0.24$, $p < 0.01$). This indicates when teachers have a growth mindset, they are more likely to grasp a more sophisticated belief system and vice versa. The indirect effect of teachers' knowledge of neuroplasticity on their epistemological belief system *via* mindset was −0.17. These findings are in line with the current literature. Multiple empirical research has suggested that teachers and students with a growth mindset, show more sophisticated beliefs and effective actions and characters (Aronson et al., 2002; Blackwell et al., 2007; Rissanen et al., 2018a,b, 2019, 2021; DeLuca et al., 2019; Dweck and Yeager, 2019; Burnette et al., 2020; Yeager and Dweck, 2020; Wang et al., 2021). These findings show that teachers' mindset has a significant effect on their pedagogical thinking, decisions, and actions toward students.

We further did a descriptive analysis of data to study how teachers with correct (good) and incorrect (poor) knowledge of neuroplasticity distributed across mindset and epistemological belief system. The results proved the same trend as discussed above. In other words, teachers with correct knowledge of neuroplasticity were mostly distributed across sophisticated beliefs and growth mindset. However, 36.6% and 30% of teachers with good knowledge of neuroplasticity were found to have a fixed mindset and a naïve epistemological belief system, respectively. One reason might be due to methodological issues. In quantitative research, when data are collected by a survey with different statements, participants might have a wrong perception of statements. The other reason could be related to the general belief system of the participants rooted in their social and cultural background. When teachers have a strong personal belief system, they may resist against scientific facts and reject integrating them into their pedagogical decisions.

Implication

Theoretical application

In line with the existing literature discussed, we agree that teachers' knowledge of neuroplasticity, epistemological belief system, and mindset are all important variables that have significant effects on their pedagogical practice. However, in most previous studies, the epistemological belief system was examined as a predictor of other traits and performance (e.g., Yilmaz-Tuzun and Topcu, 2008; Demirbag and Bahcivan, 2022). In a very basic study, Schommer (1993) found that students academic achievement were regressed on their epistemological beliefs: The less the students believed in quick learning, the higher the GPA they acquired. Mindset or implicit theory of intelligence was also found to play a predicting role in previous empirical studies (Aronson et al., 2002; Good et al., 2003; Blackwell et al., 2007; Zhang et al., 2019). In many studies, Dweck examined how students' mindset influences the ways they do different tasks. Yeager and Dweck (2020) reviewed different studies from different contexts and concluded that mindset is a predicting phenomenon for outcome and achievement. In the present research, we argued that these variables have different epistemic positions where teachers' knowledge of neuroplasticity is superior to mindset and epistemological beliefs. "Knowledge has been typically associated with genuine or scientific cognition that can provide truth whereas belief has been thought to present mere appearances or subjective opinion, usually founded on sense perceptions" (Kim, 2018). In line with the premise that knowledge shall be superior to a personal belief in teaching, we examined a model consisting of teachers' knowledge and beliefs in which teachers' knowledge of neuroplasticity was hypothesized to have effects on their mindset and epistemological belief systems. So, in this research we implicitly addressed the following concern and problem in the literature to propose a new and different conceptual model: If epistemological belief system and mindset predict individuals' performance, then how can we help students and teachers develop a sophisticated epistemological belief system and growth mindset? Based on the results of the present study, promoting teachers' knowledge of neuroplasticity helps them become practitioners with a more sophisticated epistemological belief system and growth mindset. Therefore, we have theoretically proposed a conceptual hierarchy to explain the epistemic relationship between teachers' knowledge of neuroplasticity, their mindset, and their epistemological belief system.

Practical application

Since the 1970s, there has been a cognitive shift in research on teaching, arguing that teachers are no longer the consumers of knowledge produced by university researchers but are in the epistemological position of crafting knowledge for teaching (Connelly and Clandinin, 1985; Elbaz, 1991). The core of this shift was to claim that teachers can develop personal and practical knowing while engaging in teaching (Gholami and Husu, 2010). Teachers' mindset and epistemological belief system can be considered a significant part of teachers' personal and practical knowing. Our findings showed that teachers' knowledge of neuroplasticity may help teachers to develop a sophisticated belief system and growth mindset. So, based on the results of this research, policymakers should integrate neuroplasticity knowledge into in-service teachers' professional development for supporting and developing teachers' personal and practical knowing. In addition, based on the results of this study, teacher educators should integrate educational neuroscience as a fundamental dimension of teacher education programs. In addition to pedagogical content knowledge, general pedagogical knowledge, and subject knowledge, knowledge of the brain and neuroplasticity should receive an epistemic identity in teaching studies and the teacher education curriculum.

Limitations

The present research has two basic limitations. The structural relationship between teachers' neuroplasticity knowledge, epistemological belief system, and mindset was examined for the first time in this research and a limited educational context. So, the results should be generalized with caution. In addition, we suggest other researchers re-examine or re-design this model for more empirical reliability and validity. We also found that a significant percentage of teachers with correct or good knowledge of neuroplasticity have a fixed mindset and a naïve epistemological belief system. We believe this might be due to teachers' social and cultural belief systems. Because social and cultural beliefs are a deeper part of teachers' belief systems, there should be further qualitative research to study why teachers with good knowledge of neuroplasticity still have a fixed mindset or a naïve epistemological belief system.

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 were not required for the study on human participants in accordance with the local legislation and institutional requirements. Written informed consent from the patients/ participants or patients/participants legal guardian/next of kin was not required to participate in this study in accordance with the national legislation and the institutional requirements.

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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Supplementary material

The Supplementary material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fpsyg.2022.1042891/full#supplementary-material

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TYPE Systematic Review
PUBLISHED 28 March 2023
DOI 10.3389/fpsyg.2023.1119551

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OPEN ACCESS

EDITED BY
Gregory Siy Ching,
National Chengchi University, Taiwan

REVIEWED BY
Miriam Agreda Montoro,
University of Jaén, Spain
Azzeddine Boudouaia,
Zhejiang University, China
Wayan Sintawati,
Nanjing Normal University, China
Denok Sunarsi,
Pamulang University, Indonesia

*CORRESPONDENCE
Rafel Meyerhofer-Parra
✉ rafel.meyerhofer@udg.edu

SPECIALTY SECTION
This article was submitted to Educational Psychology, a section of the journal Frontiers in Psychology

RECEIVED 08 December 2022
ACCEPTED 28 February 2023
PUBLISHED 28 March 2023

CITATION
Meyerhofer-Parra R and González-Martínez J (2023) Transmedia storytelling usage of neural networks from a Universal Design for Learning perspective: A systematic review. *Front. Psychol.* 14:1119551.
doi: 10.3389/fpsyg.2023.1119551

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Transmedia storytelling usage of neural networks from a Universal Design for Learning perspective: A systematic review

Rafel Meyerhofer-Parra* and Juan González-Martínez

Department of Pedagogy, University of Girona, Girona, Spain

The use of transmedia storytelling (TST) experiences is increasingly common in today's media ecology. Mediated by participatory culture, the role of the prosumer, and competency processes that connect with the reality of learners, the incorporation of storytelling motivates and deploys diverse didactic strategies. Considering the *engagement* generated by these strategies, and the need to promote literacies to provide competences to a plural society, a systematic review of the literature on transmedia storytelling experiences from the perspective of universal design for learning (UD-L) using PRISMA is carried out: *a priori*, we start from the idea that, if UD-L is based on the principles of educational neuroscience and TST, in turn, concretizes some of the guidelines of UD-L, TST can naturally result in a didactic approach that capitalizes on educational neuroscientific knowledge in a harmonious way with the digital context in which we live. The review analyzes a total of 50 articles from four databases: ERIC, Scopus, Web of Science, and Dialnet. The results show a low development of the checkpoints of the UD-L guides, and it is concluded that the most worked checkpoints are those closest to the definition of transmedia storytelling, followed by the foundational aspects of UD-L and, finally, aspects of access. Engagement is reflected in the experiences, but scaffolding is required to consolidate learning. In addition to this is the need to guarantee a true participatory culture, which requires the integration of more elements that incorporate accessibility into didactic strategies, offering learning possibilities for different styles and forms.

KEYWORDS

transmedia storytelling, universal design for learning, neuroscience, transmedia learning, teaching and learning (processes and methodology), active learning

1. Introduction

This systematic literature review aims to identify the use of neural networks during transmedia storytelling experiences from a universal design for learning (UD-L) perspective.

The use of didactic strategies based on storytelling in teaching and learning processes is common, as it is a valuable resource for developing an affective–emotional link with the contents to be worked on Bruner (1986), Egan (1986). Storytelling has evolved from analog to digital and from digital to transmedia. Initially through a process of digitalization, then with the arrival of the internet and now with social media, new forms of consumption and participation are emerging, where users can assume the role of prosumer: not only consuming resources but also participating fully in the creation and deployment of them (Toffler, 1980). In order to enable full participation in this new media ecosystem, there is an emerging educational need to integrate these competences and make them literate in formal educational processes, reinforcing—and in some cases laying the foundations for—the development carried out in informal and non-formal learning contexts, and thus connecting their learning with their reality outside school (Jenkins, 2006; Jenkins et al., 2009; Scolari, 2013, 2018; Jenkins and Ito, 2015; Faria-Ferreira et al., 2021).

In addition to all of this is a great opportunity: working in a transmedia way opens up many possibilities for personalization and adaptation of the learning process according to the educational needs required (Pence, 2012; Rodrigues and Bidarra, 2014, 2015; Gambarato and Dabagian, 2016; Sánchez-Caballé and González-Martínez, 2022). Moreover, in such possibilities, the UD-L paradigm finds a methodology that fits very well with the transmedia approach almost "naturally," without the teacher having to force excessively to seek convergence with the principles of universality (González-Martínez, 2022): Elements that transmedia narratives offer through participatory culture, a prosumer role, and multiple media through which a story unfolds (Pineda Acero et al., 2018), all at the learner's choice to a large extent and with remarkable flexibility (González-Martínez, 2022). In that sense, UD-L is an approach that allows "to maximize learning at individual paces," offering different entry and exit points to the learning process, offering a wide spectrum of modes of representation, consumption, and strategies for learning, so that each learner can roam within those possibilities and not only learn according to his or her uniqueness but also his or her interests. Moreover, it has, at its core, the attempt to capitalize on the knowledge generated by both experience and research and, as mentioned earlier, advances in educational neuroscience, which explain how we learn (Rose et al., 2006; Robinson and Wizer, 2016; Yuan et al., 2017). At its core, UD-L proposes to be guided, in the didactic design of learning experiences, by three principles, which are broken down into different (more concrete) lower order rules or recommendations: providing multiple forms of representation (principle 1), action and expression (principle 2), and engagement (principle 3). In addition to this, of course, in order to seek the maximum use of the different neural networks and their different weights in the different moments and elements of learning (Rapp, 2014; Alba Pastor, 2016; Castro and Rodríguez, 2017). We would say, then, chaining syllogisms, that transmedia storytelling is an intuitive way of aligning with the principles of UD-L and, therefore, it is sensible to think that it can also be a didactic way of harmonizing with the advances in educational neuroscience (Savia, 2015, 2018).

In summary, both transmedia storytelling and UD-L, insofar as they offer a great multimodality of possibilities in educational practice, are very interesting from a neuroscientific perspective, although we know little about these aspects in practice: What are the neural networks they focus on through their educational proposals? Do they work on affective, strategic, and recognition networks? Within each network: What elements do they develop?

It is well known that transmedia storytelling generates strong engagement, but there are authors who go a step further and link transmedia strategies to Zull's cone of emotion and Kolb's learning cycle (Kalogeras, 2013). Although, what this engagement entails has not been studied in such detail, since a lot of transmedia storytelling experiences lean toward sharing the practice rather than a reflection toward the methodological benefits, let alone what strategies and forms of representation they use if it is analyzed from a UD-L perspective.

TABLE 1 Research questions of the study.

	Research questions
1	How are recognition networks used in Transmedia Storytelling experiences based on UD-L principles?
2	How are strategic networks used in Transmedia Storytelling experiences based on UD-L principles?
3	How are affective networks used in Transmedia Storytelling experiences based on UD-L principles?

In view of the aforementioned points, the current systematic review of the literature raises the following research questions, which can be observed in Table 1.

2. Methods

In view of the initial research questions established, it is considered that the systematic literature review (SLR) using the PRISMA guidelines is a feasible method that will enable to locate and analyze the most relevant documents regarding the research questions while offering clear, useful, and replicable access to the research process (Okoli and Schabram, 2010; Urrútia and Bonfill, 2010). An SLR is "a systematic, explicit, comprehensive, and reproducible method for identifying, evaluating, and synthesizing the existing body of completed and recorded work produced by researchers, scholars, and practitioners" (Okoli, 2015, p. 880).

2.1. Search strategy

The search for theoretical essays and studies related to transmedia storytelling was carried out in four electronic databases with the terms of "transmedia" AND "education". The search choice was "transmedia" and not "*transmedia storytelling*," to widen up the initial identification and screen it manually rather than with the searching tools themselves, guaranteeing that only documents clearly related to transmedia storytelling experiences. In addition, it helped to use the same keywords in all the databases, which could have been an issue while using non-English databases. Since one of the databases is in Spanish, the decision was relevant to recollect articles that translated "storytelling" to "narratives".

2.2. Information sources

The databases chosen were Web of Science for its quality and inclusion of all types of publications; Scopus, for its recognized content of quality scientific articles; Educational Resources Information Center (ERIC), for being a repository focused on research in the field of education; and Dialnet, a database with documents published in Spanish, since large numbers of publications in the field of transmedia storytelling are in this language.

TABLE 2 Quality criteria questions and scores.

	Question	Score
1	Was the purpose of the paper stated clearly	2
2	Was the rationale for implementing a transmedia experience intervention described	2
3	Were the steps of the intervention clearly outlined	4
4	Were the media/s used in the experience clearly identified	2
5	Were the principles of UD-L integrated in the experience	2
6	Does the document describe the impact of the transmedia experience	2
7	Does the user participate in the unfolding of the story?	2

Based on van Eerd et al. (2010) and Mahood et al. (2013).

2.3. Selection process

The selection criteria used were based on van Eerd et al. (2010) and Mahood et al. (2013) and were open to all types of published publications (book chapters, conferences, and PhD Theses.) but must define or include implicitly or explicitly what they understand as transmedia storytelling. Documents not in English or Romanic languages were excluded.

The document relevance review was first based on the review of the abstract or, if necessary, the full document. Pairs of reviewers blindly voted to take into consideration if the document included a definition of transmedia storytelling or, alternatively, that they use the concept of transmedia storytelling and describe, more or less explicitly, what they are referring to while using the concept. Reviewers were guided initially by definitions in the literature such as Jenkins (2006) and Phillips (2012) but also by the identification of coexistent concepts such as remixing, participatory culture, and prosumer (González-Martínez et al., 2019).

Once the first round of blind votes was conducted, they were merged. In case of agreement, the document was included or excluded from retrieval. If there was not an initial consensus between the two researchers, a third peer blindly voted for three different options: inclusion, exclusion, or doubt, leading the latter to a process of discussion of how to proceed regarding that article. Only documents with enough detail on content were judged according to the quality criteria, which can be seen in Table 2.

Partial scores (half value) were possible for questions 1–5. A maximum of 16 points can be achieved. Data extraction was performed with those documents receiving the quality criteria score of 10 or more (out of 16). In addition, it was initially planned that if one of the reviewers identified a document as rich content referring to its transmedia storytelling experience, or its consideration toward UD-L, it would be retained for data extraction even if the quality score was lower than 10. In the end, this measure was planned but not used, since all the documents identified as relevant by the reviewers had a high-quality score.

A more detailed explanation of the procedure, expanding the information on the identification and screening process, can be observed in Figure 1, and a synthesis of the included studies is shown in Table 3.

2.4. Data collection process

In order to collect information through which to answer the research questions, we use the UD-L guidelines presented by CAST (2018), in which there are three levels under which to collect transmedia experiences, their use of UD-L principles, and how they connect to networks.

On the first level, there are three networks (*recognition*, *action and expression*, and *engagement*). On the second level, the nine UD-L guidelines related to the three networks (*recognition*: perception, language, and symbols; *action and expression*: comprehension, physical action, expression and communication, and executive functions; and *engagement*: recruiting interest, sustaining effort and persistence, and self-regulation). The neural networks and the guides also have proposed checkpoints, which can be seen in detail in Table 4.

To collect the results of the experiences, it was decided to use three categories: explicit, implicit, and not developed. In this way, it will be possible to perceive the multiplicity of scenarios within the experiences, as well as the combination of different elements within the UD-L paradigm, understanding it as an opportunity to see which elements to incorporate within the experiences. An experience does not necessarily have to develop all the elements: a better experience is not one that includes more checkpoints within the guidelines, but tracking its use can help to see future perspectives within the application of UD-L in the educational field and, specifically, in the application of transmedia storytelling experiences.

In addition, it was decided to use another categorical system offered by CAST (2018) to contrast the information. This is why it is then analyzed according to *representation, action and expression, and engagement* and subsequently analyzed using access, which encompasses G1, G4, and G7; build, which contains G2, G5, and G8; and internalize, which has the last three: G3, G6, and G9.

3. Results

3.1. Action and expression, engagement, and representation

As can be seen in Figure 2, with reference to the checkpoints sorted according to the categories of action and expression, engagement, and representation, there is a large divergence between the categories.

3.1.1. Representation

Focusing initially on the representation category, it can be observed that in guideline 1, which includes alternative ways of providing information by visual or auditory means, practically no use is found in the experiences collected. Among the few experiences that include it are Faria-Ferreira et al. (2021), which provide alternative ways of reading, such as film fragments that correspond to the chapter, and an e-book, to change the sequence

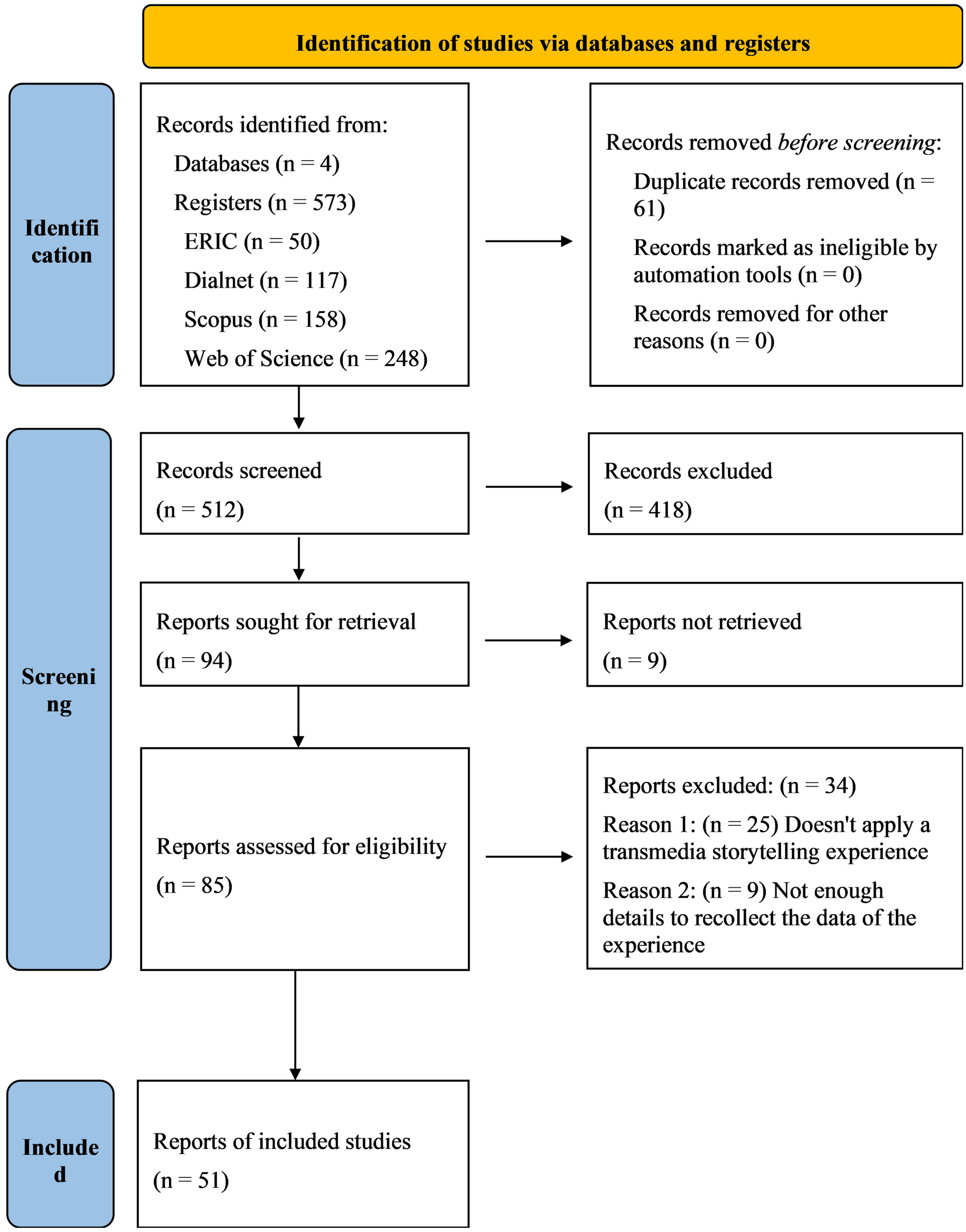

FIGURE 1
Identification of studies via databases and registers using PRISMA 2020 (Page et al., 2021). For more information, visit: http://www.prisma-statement.org/.

of the story without changing its meaning. Another case that seeks to offer alternatives is Scolari et al. (2019), with hypertextual adaptation by students to facilitate each other's reading, and then exploring adaptations of the work into graphic novels, narrative illustrations, and other graphic works. In fact, literally one of the activities proposed is the adaptation of graphic media, which in addition to offering alternatives to visual information, offers the opportunity to appropriate the text, generating a more immersive educational experience and thereby increasing intrinsic motivation with the learning process. In Albarello and Mihal (2018), it is also possible to identify how crossmedia elements are used to offer different access points to the information presented. In reference to checkpoint C.1.3, few alternatives for visual information are detected, and the podcast format is little identified as an option deployed to facilitate visual to auditory information.

Similarly, in guideline 2, a minority use is identified in the experiences, but both C2.4, which refers to *understanding across languages*, and C2.5, which refers to *illustrate through multiple*

TABLE 3 List of included studies.

Num.	References	Doc. type	Educational context/ level	Geographical context
[1]	Diéguez (2014)	Paper	Master and undergraduate	Hungary and USA
[2]	Jover et al. (2015)	Paper	Secondary	Spain and Chile
[3]	Peña-Acuña (2021)	Paper	Primary and Secondary	Spain
[4]	Faria-Ferreira et al. (2021)	Paper	Primary	Portugal
[5]	Vásquez Arias and Montoya Bermúdez (2016)	Paper	Secondary	Colombia
[6]	Rovira-Collado et al. (2016)	Paper	University—Master	Spain
[7]	Charria Castaño (2017)	Paper	Secondary	Colombia
[8]	Molas Castells and Rodríguez Illera (2018)	Paper	Secondary	Spain
[9]	Arrausi Valdezate and Cerro Villanueva (2017)	Paper	Non formal—Linked to business	Spain
[10]	Gutiérrez Pequeño et al. (2017)	Paper	University—undergraduate	Spain
[11]	Molas Castells and Rodríguez Illera (2018)	Paper	Secondary	Spain
[12]	Gómez-Trigueros et al. (2018)	Paper	University—master	Spain
[13]	de la Puente (2018)	Paper	University—graduate students	Argentina
[14]	Scolari et al. (2019)	Paper	Secondary	Spain
[15]	Amador-Baquiro (2018)	Paper	Primary and secondary	Colombia
[16]	Albarello and Mihal (2018)	Paper	Primary and secondary	Argentina
[17]	Alonso and Murgia (2018)	Paper	Secondary	Argentina
[18]	Tomšič Amon (2019)	Book chapter	University—undergraduate	Slovenia
[19]	Tomšič Amon (2020)	Paper	University—undergraduate	Slovenia
[20]	Gambarato and Dabagian (2016)	Paper	Not defined	Canada and USA
[21]	Hovious et al. (2021)	Paper	Secondary	USA
[22]	Reid and Gilardi (2016)	Book chapter	University—undergraduate	Japan
[23]	Scolari et al. (2020)	Paper	Secondary	Spain
[24]	McCarthy et al. (2018)	Paper	Pre-primary	USA
[25]	Stansell et al. (2015)	Paper	Primary and secondary	USA

(Continued)

TABLE 3 (Continued)

Num.	References	Doc. type	Educational context/ level	Geographical context
[26]	Benedict et al. (2013)	Paper	University—undergraduate	USA
[27]	Rodríguez-Illera and Molas-Castells (2014)	Paper	Secondary	Spain
[28]	Paulsen and Andrews (2014)	Paper	Pre-primary	USA
[29]	Kalogeras (2013)	Paper	University	UK
[30]	Fleming (2013)	Paper	Secondary	USA
[31]	Myers (2020)	Paper	Non formal context	Australia
[32]	Wiklund-Engblom et al. (2014)	Paper	University—undergraduate	Finland
[33]	Coles and Bryer (2018)	Paper	University—undergraduate	UK
[34]	Lachman et al. (2010)	Paper	Secondary	Canada
[35]	Wiklund-Engblom et al. (2013)	Conference paper	University—undergraduate	Finland
[36]	Ellis et al. (2018)	Paper	Secondary	USA
[37]	Berezina (2020)	Paper	University—undergraduate	Malaysia
[38]	Perry (2020)	Paper	University—undergraduate	Malaysia
[39]	Arkhangelsky et al. (2021)	Paper	Primary	Russia
[40]	Rodrigues and Bidarra (2014)	Paper	Secondary	Portugal
[41]	Raybourn (2014)	Paper	Non formal—Army	USA
[42]	Cronin (2016)	Paper	University	USA
[43]	Heilemann et al. (2018)	Paper	Non formal—medical use for women with depression	USA
[43]	Anguita Martínez et al. (2018)	Paper	University—undergraduate	Spain
[44]	Fernández Díaz et al. (2019)	Paper	University—undergraduate	Spain
[45]	Rosenfeld et al. (2019)	Paper	Preschool	USA
[46]	Djonov et al. (2021)	Paper	Pre-primary	n.d.
[47]	Marín-García and Gómez (2014)	Paper	University—undergraduate	Spain
[48]	Rodrigues and Bidarra (2019)	Conference paper	Secondary	Portugal
[49]	Peralta García and Ouariachi Peralta (2015)	Paper	Post secondary education	Spain
[50]	Bárcenas López et al. (2018)	Paper	Upper secondary	Mexico
[51]	Herrero (2019)	Book chapter	Secondary	UK

media, are used significantly more, being found to be developed in 17 and 21 experiences, while the other checkpoints were used between one and two times.

Within C2.3, *support decoding of text, mathematical notation, and symbols*, Tomšič Amon (2020), and his deployment of an experience that asks students to hybridize artistic and mathematical knowledge, so that they have to precisely identify the mathematical figures in a series of images, stands out. They find this particularly challenging to combine and are given both support to do this, and different levels of difficulty to work through. In C2.4, *promote understanding across languages,* and in C2.5, *illustrate through multiple media*, the cases identified are higher. Most of the cases identified in C2.4 are part of transmedia experiences linked to second language learning, and that is why the checkpoint is often more or less explicitly identified. Regarding C2.5, some studies make it more explicit than others: For instance, some initially present a map, graphic, or system to present what and how to work on it (Vásquez Arias and Montoya Bermúdez, 2016; Alonso and Murgia, 2018; de la Puente, 2018; Ellis et al., 2018; Pineda Acero et al., 2018; Rodrigues and Bidarra, 2019; Perry, 2020), which can also be related to C3.3 *Guide information processing and visualization*. The last guideline within representation is comprehension, and in it we can identify a higher use, finding it in more than half of the experiences analyzed. These are checkpoints that refer to prior knowledge (C3.1), patterns and relationships (C3.2); processing and visualizing information (C3.3); and its transfer (C3.4) and are considered by the experiences much more than the other guidelines within the same category.

During the screening process, it has been identified that transmedia storytelling often wants to connect informal and formal educational contexts, which connects with C3.1, C3.2, and C3.4, (Marín-García and Gómez, 2014; Gutiérrez Pequeño et al., 2017; González-Martínez, 2022), by choosing competences acquired outside and integrating them in the classroom (Albarello and Mihal, 2018; Alonso and Murgia, 2018; Scolari et al., 2020), or simply because the narrative moves the reflection to the present—students in the experiences often have to incorporate their prior knowledge for the development of the activity (Rodríguez-Illera and Molas-Castells, 2014; Albarello and Mihal, 2018; Alonso and Murgia, 2018; Gómez-Trigueros et al., 2018; Molas Castells and Rodríguez Illera, 2018; Scolari et al., 2019; González-Martínez, 2022). In addition, there is a latent need for *scaffolding,* which is not always present and assumes competences and literacies that they do not necessarily need to have (Kalogeras, 2013; McCarthy et al., 2018).

3.1.2. Action and expression

Moving on to the *Action category*, the most represented checkpoints in the documents included in the SLR are identified. Starting with guideline 4, we find with 43 (29 explicit and 14 implicit) *vary the methods for response and navigation* and with 22 (8 explicit and 14 implicit) the C4.2 *Optimize access to tools and assistive technologies*. There is a very important difference between the two elements of the category, and it is especially noteworthy that most of the transmedia storytelling experiences. Both highlight their implicit use, often behind the alternatives that can be offered within digital tools, but especially in the case of C4.1, the fact that the learner can become a prosumer and the center of their learning process, where they can choose the media for their learning process, makes it easier for them to find alternatives within the requirements that suit their particularities.

Entering guideline 5, there is a disparity in its use: C5.1 and C5.2 are widely used, with C5.1 being one of the strong points in terms of composition in multiple media: illustrations, storyboards, films, video games, augmented reality games, simulations, chats, blogs, and comics, and in the case of C5.2 its use is also outstanding, but above all for the possibility of using hypertexts, concept maps, and many web resources. On the contrary, C5.3 is related to establishing graduated levels of support for practice and development, practically not identified in the experiences, with a very important contrast from 9 and 6 not used in the first two, to 37 not used for C5.3. In reference to C5.3, although an effort is made to try to give examples of good practices of transmedia narratives, or a certain background prior to the development of the activity, there is often no scaffolding either of competence or of the activity.

In the last guideline within action and expression, G6. *For executive functions, there* is a great heterogeneity of explicit, implicit, and not developed uses. Altogether, these items identify an inherent limitation in the research process: when they describe or talk about the experience, they do so as an object of study about which research questions were asked, and not always as a mere description of the activity carried out in the educational context. Therefore, some elements such as the setting of objectives, the setting of strategies, and the deployment of these and the other checkpoints in guideline 6 may be under-represented.

3.1.3. Engagement

With regard to *guideline 7, recruiting interest,* C7.1 and C.7.2 are mostly used, with high values referring to individual decision and relevance or authenticity, while C7.3 refers to factors that will minimize distractions and are not developed in 46 of the 50 articles in the systematic review. Again, given that C7.1 and C7.2 are closely linked to the possibility of prosumption and an active role in the learner's unfolding of the story, it is common for them to be worked out, although it is cast in more open, and not so constantly guided transmedia experiences. In some cases (Albarello and Mihal, 2018; McCarthy et al., 2018; Rodrigues and Bidarra, 2019; Scolari et al., 2019), a very wide range of possibilities is identified. Even by proposing itineraries with compulsory and optional options, so that students can deploy what most motivates them and promote their autonomy both as a group and as individuals.

In guideline 8, there is a disparity of explicit, implicit, and not developed uses. In C8.2 and C8.3, a majority of the use of checkpoints can be seen (36 and 38), while in C8.1 it is moderate (23) and in C8.4 it is very low (15). In fact, it makes sense that both C8.2 and C8.3 are in line with each other, given that they are about varying demands and resources in order to optimize the challenge and to collect collaboration and community: two items closely linked to Jenkins' (2006) ideas on participatory culture and one of the phenomena he describes as paradigmatic in the current media ecology. In contrast, C8.1 and C8.4 refer more to the assessment process, which can often fall more on the teacher.

TABLE 4 Networks, guidelines, and checkpoints collected during the screening process of the systematic review according to explicit (E), implicit (I), and not developed (ND).

Network	Guidelines	Checkpoints	E	I	ND
Representation	G1. Perception	C1.1. Offer ways of customizing the display of information	14	4	33
		C1.2. Offer alternatives for auditory information	4	2	45
		C1.3. Offer alternatives for visual information	3	2	46
	G2. Language and Symbols	C2.1. Clarify vocabulary and symbols	1	1	49
		C2.2. Clarify syntax and structure	1	0	50
		C2.3. Support decoding of text, mathematical notation, and symbols	0	1	50
		C2.4. Promote understanding across languages	1	10	40
		C2.5. Illustrate through multiple media	7	10	34
	G3. Comprehension	C3.1. Activate or supply background knowledge	13	21	17
		C3.2. Highlight patterns, critical features, big ideas, and relationships	18	8	25
		C3.3. Guide information processing and visualization	24	6	21
		C3.4. Maximize transfer and generalization	7	14	30
Action and expression	G4. Physical Action	C4.1. Vary the methods for response and navigation	29	14	8
		C4.2. Optimize access to tools and assistive technologies	8	14	29
	G5. Expression and Communication	C5.1. Use multiple media for communication	36	6	9
		C5.2. Use multiple tools for construction and composition	38	7	6
		C5.3. Build fluencies with graduated levels of support for practice and performance	7	7	37
	G6. Executive Functions	C6.1. Guide appropriate goal setting	15	22	14
		C6.2. Support planning and strategy development	16	14	21
		C6.3. Facilitate managing information and resources	13	11	27
		C6.4. Enhance capacity for monitoring progress	8	8	35
Engagement	G7. Recruiting interest	C7.1. Optimize individual choice and autonomy	12	19	20
		C7.2. Optimize relevance, value, and authenticity	10	23	18
		C7.3. Minimize threats and distractions	0	5	46
	G8. Sustaining effort and persistence	C8.1. Heighten salience of goals and objectives	15	8	28
		C8.2. Vary demands and resources to optimize challenge	25	11	15
		C8.3. Foster collaboration and community	33	5	13
		C8.4. Increase mastery-oriented feedback	4	11	36
	G9. Self-regulation	C9.1. Promote expectations and beliefs that optimize motivation	9	18	24
		C9.2. Facilitate personal coping skills and strategies	8	20	23
		C9.3. Develop self-assessment and reflection	14	16	21

Retrieved from CAST (2018).

To conclude with the analysis of checkpoints, the last of the engagement network guidelines is self-regulation. In this guideline, there is a moderate use of checkpoints, but they are mostly detected implicitly and identified in the discourse, rather than explicitly (C9.1. 9–18; C9.2. 8–20; C9.3. 14–16). Often the elements of *self-regulation* were identified during the review process through

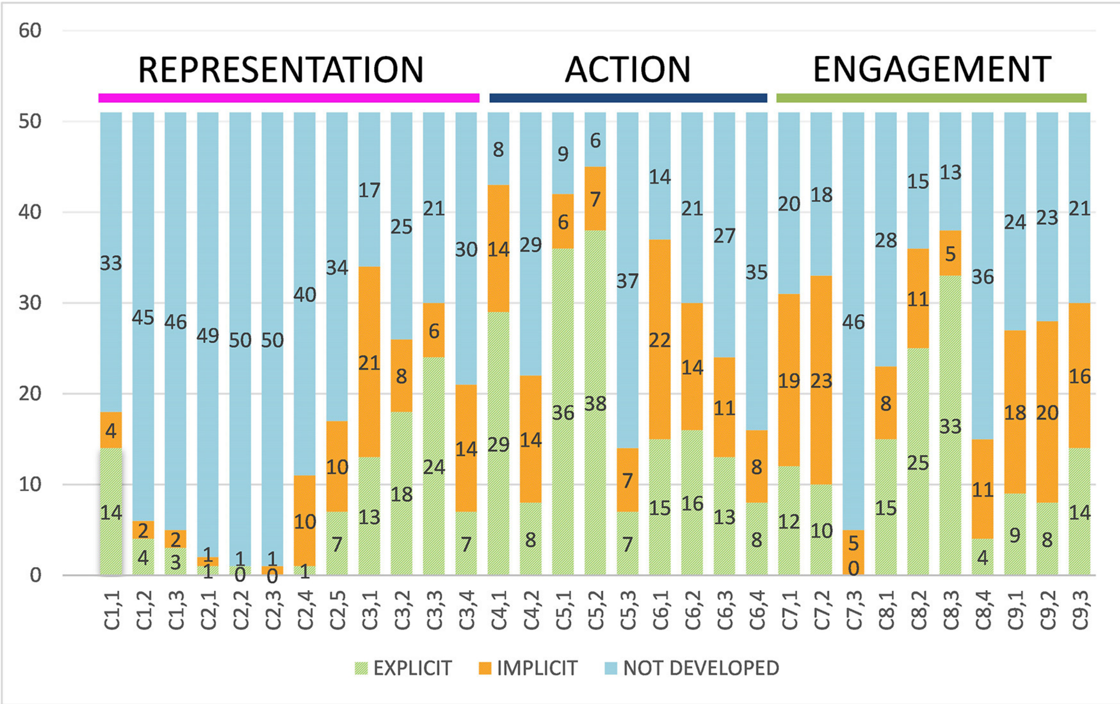

FIGURE 2
Explicit, implicit, and not developed uses of the checkpoints of the three networks.

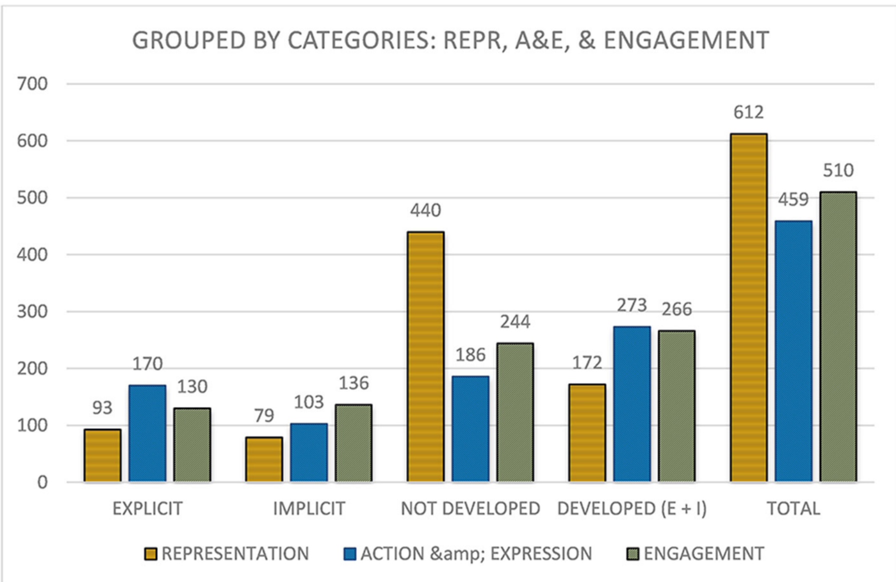

FIGURE 3
Identified uses of checkpoints grouped by the three networks.

the description of what tasks were given to learners, rather than through a process of making them explicit or inviting them to perform those tasks. One of the elements claimed in the reflections is the aspect of motivation (Albarello and Mihal, 2018; Heilemann et al., 2018; McCarthy et al., 2018; Molas Castells and Rodríguez Illera, 2018; Scolari et al., 2019; Perry, 2020; Hovious et al., 2021).

3.2. Categories from a general perspective

Moving toward the analysis of the guidelines in a more general perspective, and taking into consideration the aggregate data of the aforementioned checkpoints seen in Figure 3, we can raise different considerations.

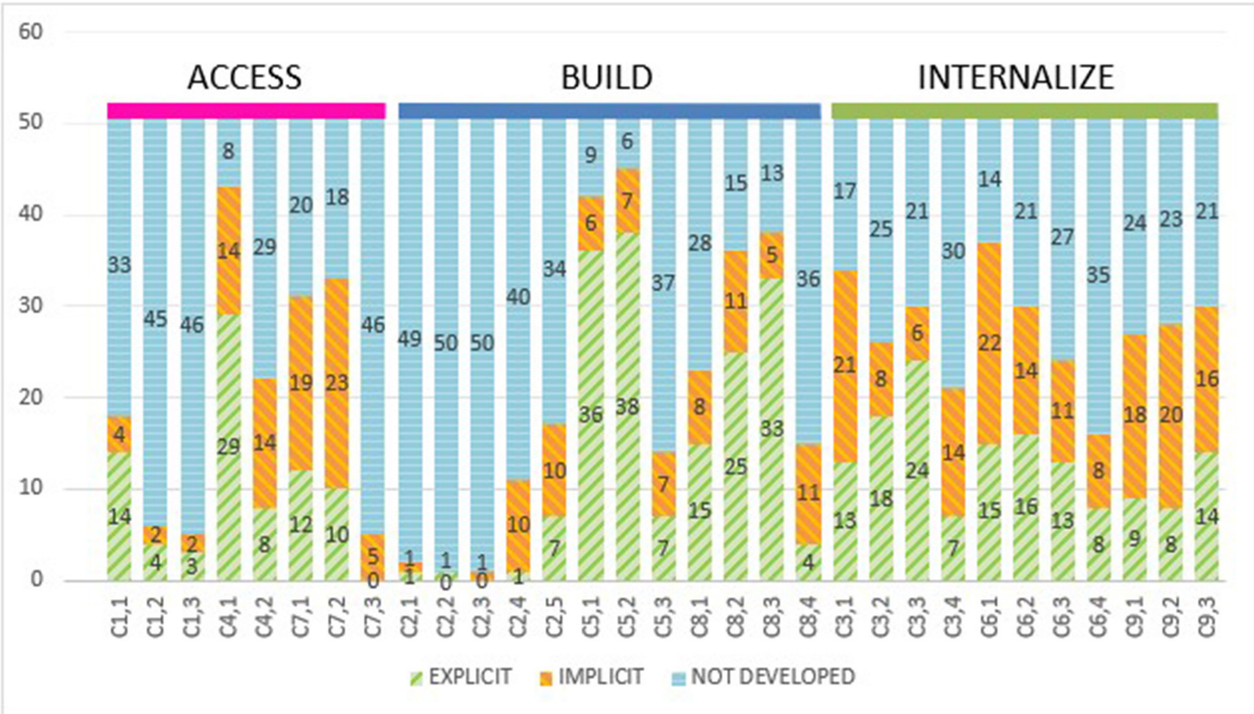

FIGURE 4
Explicit, implicit, and not developed uses sorted by *access, build, and internalize* categories.

TABLE 5 Percentage of explicit, implicit, and not developed use.

	Explicit (%)	Implicit (%)	Not developed (%)
Access	19.61	20.34	60.05
Build	27.45	12.58	59.97
Internalize	25.85	28.16	45.99
Engagement	25.49	26.67	47.84
Representation	15.20	12.91	71.89
Action and expression	37.03	22.44	40.53

First, as can be seen in Figure 3, the representation network has the most items and, therefore, a higher total aggregate (612). It is followed by *engagement* (510) and action and expression (459). Although, it is surprising how *representation* is the network with the highest number of possible points that has precisely the fewest, with 15.20% of explicit uses, 12.91% of implicit uses, and 71.89% of not developed uses. This is a very high percentage and contrasts with the other networks, which have 47.84 (*engagement*) and 40.53% (*action and expression*) of not developed.

Moving on to the *engagement* network, the figures for this network are quite different: Explicit and implicit use are quite similar (25.49 and 26.67%, respectively), totaling 52.16%, just over half of which have been explicitly identified, and only a quarter of which have been explicitly identified. Finally, with regard to the action and expression network, there is a greater explicit use of checkpoints (37.03%) and an implicit use of 22.44%, which in aggregate is the highest use identified among the three networks (59.48%).

Taking into consideration a large amount of not developed data, it is decided to expose the results also according to the *access, build, and internalize* categories.

3.3. Access, build, and internalize

As can be seen in Figure 4, access is made up of guidelines 1, 4, and 7. Looking at the explicit, implicit, and not developed uses through the access perspective, a great divergence in the data can be observed. While the checkpoints of guideline 1 have very low values, those of guidelines 4 and 7 are among the highest, which allows us to identify that the experiences may not develop some of the items in the access perspective, but do take access into consideration within their proposals, although in a way that is closer to the engagement perspective (G7) and action and expression (G4), and not to the representation perspective (G1).

As far as build is concerned, a similar situation is identified: There is a very low use of guideline 2, which corresponds to representation, but a high use of the checkpoints corresponding to action and expression (G5) and engagement (G7).

Finally, analyzing from the perspective of the internalized category, balanced use of the checkpoints corresponding to the representation (G3), action and expression (G6), and engagement (G9) is identified.

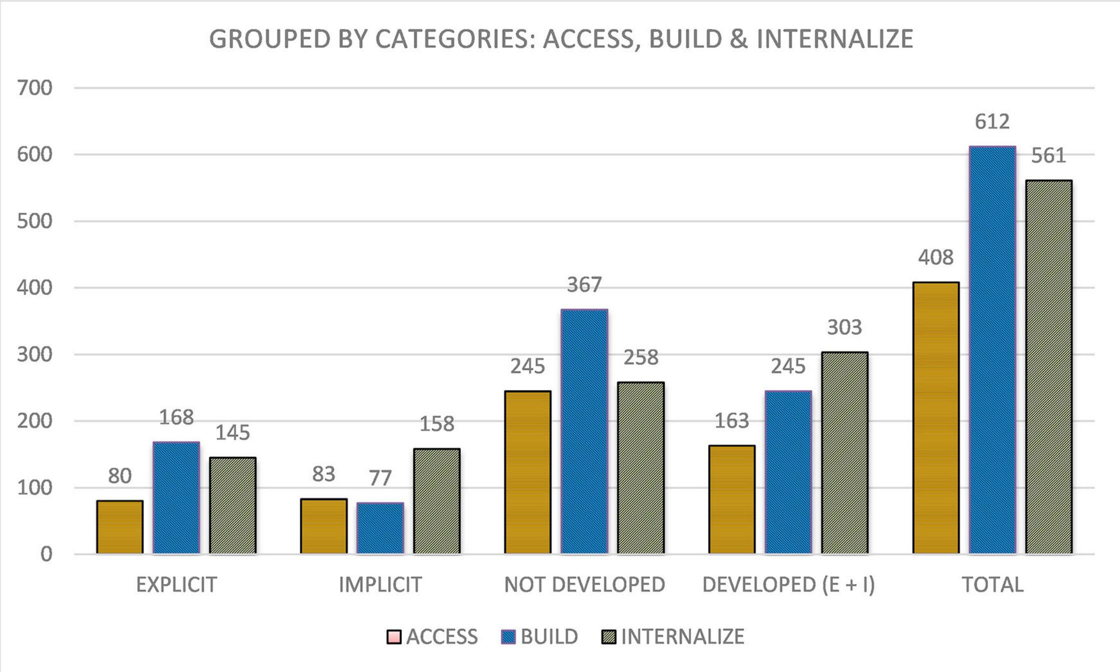

FIGURE 5
Identified uses of checkpoints grouped by access, build, and internalize categories.

If these data are observed and grouped by category, significant differences in the weighting of the categories become apparent.

As can be seen in Figure 5, first, the access category has a much smaller representation (408) compared with the build (612) and internalize (561). Going into the uses, access has a very similar explicit and implicit use (80 and 83), corresponding to 39.95% (19.61 and 20.34%, respectively) of the total, in contrast to the 60.05% of not developed (see Table 5).

Second, in the build category, explicit usage (27.45%) is significantly higher than implicit usage (12.58%), which in aggregate is 40.03%, and both the build and access categories have very similar developed—not developed data.

Finally, the *internalize category* shows very similar explicit and implicit use (25.85 and 28.16%), which are substantially higher than in the other categories, totaling 54.01%. Considering that this is the highest figure within the three grouped categories, it helps to visualize that a large number of checkpoints are not worked from the three categories.

3.4. Comparison of the categories

Note that when calculating the development in terms of the triad access, build, and internalize, the percentages are quite different from those observed in terms of *engagement, representation, and action and expression.*

Finally, focusing on the uses of the checkpoints not linked to the guidelines, in Figure 6 a great heterogeneity can be observed, and although it can be identified that the checkpoints of guidelines 2 and 1 are the least used, and those of guideline 5 are the most used. The rest are spread very thinly across the graph. At the same time, the fact that the most developed competences are identified implicitly, rather than explicitly, stands out.

4. Discussion

Based on the aforementioned results, and taking into consideration research questions 1–3, how are the different networks used?

4.1. Representation, action and expression, and engagement

With regard to the transmedia storytelling experiences collected for the systematic review, it can be stated that the *representation* network is quite underused, with 71.89% not developed. Within the transmedia storytelling experiences, it would be very positive to incorporate dynamics that take into consideration perception (G1) and language and symbols (G2).

Both guidelines are rarely used, but they are substantially different cases: In G2, we can see circumstances where it would be very complicated to give answers to the checkpoints and, again, it is not a question of always giving answers to these items, but rather of offering a teaching and learning proposal that contemplates the UD-L paradigm, not all the items are necessary for a good proposal in this framework. In the case of G2, there are few experiences linked, for example, to the field of mathematics, where it could make a lot of sense to work on checkpoint C2.1 and especially C2.3. On the contrary, in the case of G1, all the cases could develop it, and this is why it is a little more worrying not to identify it when many

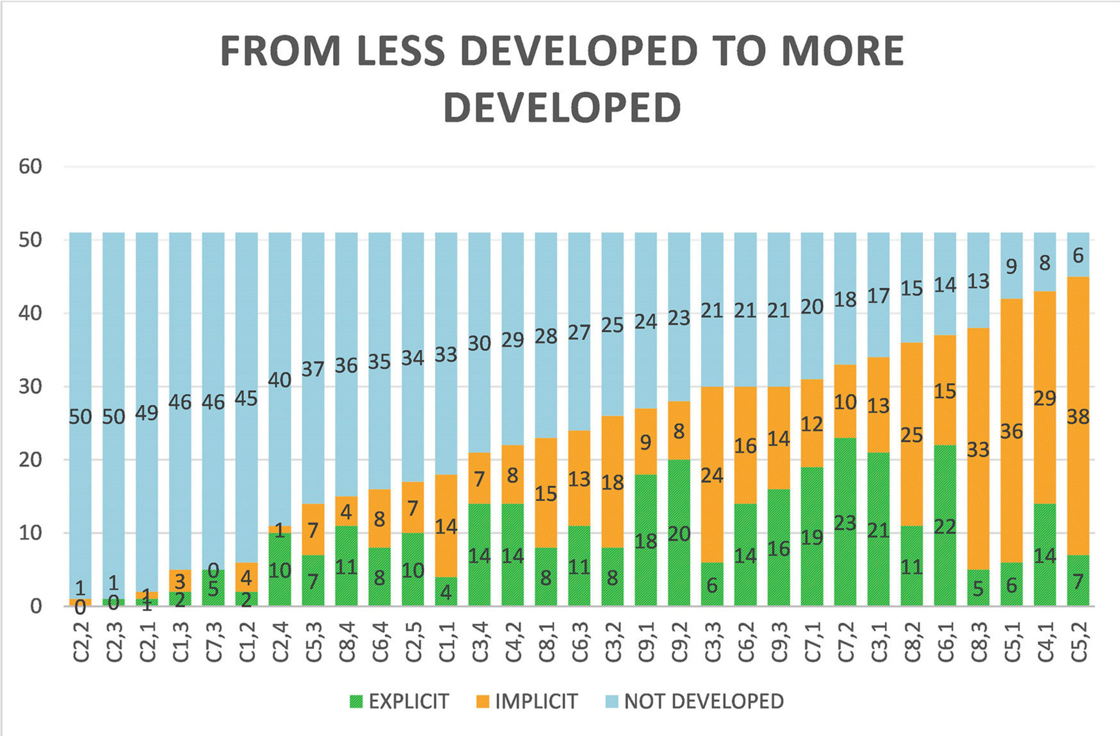

FIGURE 6
Implicit, explicit, and not developed uses. Sorted from the most to the least not developed.

of the experiences either work on the literature or on the learning of a second language.

Although, in G1's interpretation, the technological aspect plays an important role: While in an analog context, the need for explicit adaptations would be clear, existing software can mediate the proposals without the need to make an intentional choice in the learning design, as such tools exist to facilitate access.

Regarding the *action and expression* network, it is the most used network, with a total of 59.47%. We believe that this figure could be even higher, but there are two items that decrease its use considerably.

The first, *optimize access to tools and assistive technologies*, a checkpoint where again—as in the case of G2—the question emerges as to what extent the incorporation of tools is taken for granted, does not exist, or simply does not emerge in the experiences collected. The second, C.5.3. *build fluencies with graduated levels of support for practice*, comes face to face with one of the aspects highlighted in the data retrieved for the study, given that the need for appropriate scaffolding for carrying out the activities was an element mentioned in several of the experiences as a need that perhaps they had not been able to resolve adequately or that needs to be taken into consideration. At the same time, and connecting with G4, G5, and their respective checkpoints, a bottleneck effect is identified: Many of the experiences are framed in a subject and context that does not allow for interdisciplinarity, whereas it would be a very natural element of participatory culture, and necessary to incorporate different mentoring figures for different approaches to the educational phenomenon.

Finally, as far as the *engagement* network is concerned, the ideas often linked to Jenkins' (2006) idea of participatory culture are generally very much incorporated, with the exception of C7.3 *minimize threats and distractions* and C8.4 *increase mastery-oriented feedback*. Again, C8.4 has certain points of contact with the issue of evaluation, as expressed in the case of C5.3 and C7.3.

One element that the case of C7.3 raises is that it is likely to presuppose that it is not necessary to establish mechanisms for distraction, given that one of the arguments for promoting transmedia narrative dynamics in the classroom is precisely this: to incorporate a narrative element that captures the students' attention, maximizing their motivation and interest. It should be added that many of the elements of engagement recovered in this section end up being collected thanks to the selection of tools such as blogs, forums, and other spaces for reflection, co-creation, and participation among peers.

4.2. Access, build, and internalize

If we look at it from the perspective of the *access, build,* and *internalize* categories, it is clear that the access perspective is underdeveloped. As noted earlier, there are three possible situations: (1) that it has been over-emphasized or omitted as a matter of space available to explain the experiences and research that emerges from it, (2) that digitization and tools that are often included within digital media are available to partially alleviate the accessibility problem, and (3) that it has not been considered.

FIGURE 7
Checkpoints ranked according to their use from the highest to the lowest, and according to whether they are close to transmedia storytelling ideas (magenta), UD-L foundational research ideas (yellow), and accessibility (blue).

In internalize, we find a fairly balanced use of the different checkpoints, and it is striking how in the build we find a great heterogeneity of uses between checkpoints. As noted earlier in reference to the least used checkpoints, this could be due to the type of experiences that are worked on within the SLR studies.

4.3. From a global perspective

Considering the order from least to most that was previously visualized in Figure 6, it could be believed that, to a certain extent, the most used (marked in magenta in Figure 7) are those checkpoints more linked to participatory culture and to the ideas that Jenkins (2006) exposed. The aforementioned text has had a great impact on the literature and is one of the major references when talking about examples of transmedia narratives in the theoretical framework. It is, therefore, understandable that they include many of the elements of transmedia narrative expressed in their initial definition.

Following these checkpoints, others marked in yellow are identified, which are elements closely linked to the *foundational research* of the UD-L paradigm. According to the CAST (2018), these are elements rooted in aspects of neuroscience, cognitive psychology, and learning sciences.

Finally, the elements least observed in the experiences collected are those marked in blue and are related to the principle of accessibility and representation. During the SLR, we observed how the elements within the UD-L that seek to offer a multiplicity of modes of representation, monitoring, and assessment are the ones that are sometimes the most difficult to identify. These would be the ones that teachers should focus on when planning learning experiences, following the guidelines of CAST (2018) or Alba Pastor (2016), in order to better exploit the potential of transmedia storytelling from a UD-L and neuroscientific perspective.

4.4. Conclusion

In reference to the modes of representation, it is an element that is easy to integrate into a paradigm such as transmedia storytelling, where offering this multiplicity of means of representation is even an added value in the construction of the story, in working and unfolding the story through different media, and working in a crossmedia way with some elements, understanding that even working with the same content on another platform adds learning and ways of doing things that make it unique, since the channel partly defines the message (McLuhan, 1994; Dena, 2009). By the way of example, offering both the analog format of a book and its digital option, podcast, or online video explaining it, despite dealing with exactly the same content, the podcast and the physical book have very different characteristics between them, an element that we can take advantage of to generate greater engagement (especially in the autonomy of choice), but also to satisfy multiple modes, styles, and even learning rhythms.

Regarding monitoring and evaluation, it could be said that this is an element that needs to be worked on and requires more planning. In many of the activities, a more active and dynamic role in the teaching and learning processes would be positive, and simultaneously a process of co-construction among the students: Often the transmedia storytelling learning experiences are unidirectional: There is little peer evaluation and little collaboration among their projects. Small groups are proposed, allowing them to develop their competences and more active and full participation in the contents and competences to be deployed, but also more fragmented in their learning, and less connected both to the collective intelligence and to the reflections and learning of the rest of their peers.

An aspect that extends not only to the transmedia experiences identified but also to the difficulty of having sufficient information to replicate the transmedia narrative experiences analyzed, which do not offer enough information about these experiences to be able to participate in a real participatory culture where presuming, collaborating, or remixing around the existing experiences.

4.4.1. Limitations of the study and future research

To conclude, transmedia storytelling as a didactic strategy still harbors a large number of possibilities to be discovered. But in order to be able to explore it, it is necessary to increase the transparency and transfer of these experiences, so that the experiences allow us to build meaningful experiences, and to avoid mistakes already made, and to suspect options, ideas, and try to guarantee shared educational actions that create a change of grammar and dynamics linked to educational processes that are closer to the daily realities of all the participants. The processes for which one is not always prepared, and, therefore, the need, as several of the studies described—and also the foundational aspects of UD-L—for a scaffolding for the activity, in line with not assuming that, by the mere fact of being digital natives, they necessarily have a high level of digital or transmedia literacy.

Data availability statement

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

Author contributions

RM-P: conceptualization, methodology, writing—original draft, writing—reviewing and editing, and visualization. JG-M: conceptualization, methodology, writing—original draft, and writing—reviewing and editing. All authors contributed to the article and approved the submitted version.

Acknowledgments

The authors thank Marta Peracaula-Bosch for helping throughout the screening and revision process.

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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TYPE Original Research
PUBLISHED 05 May 2023
DOI 10.3389/fpsyg.2023.1139911

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Amy Corrinne Roberts,
University of Wyoming, United States

REVIEWED BY
Din-yuang Huang,
Fu Jen Catholic University, Taiwan
Sheilla Magbanua Trajera,
University of St. La Salle, Philippines

*CORRESPONDENCE
Verena Novak-Geiger
✉ Verena.Novak@aau.at

RECEIVED 07 January 2023
ACCEPTED 14 April 2023
PUBLISHED 05 May 2023

CITATION
Novak-Geiger V (2023) Prevalence of neuromyths among psychology students: small differences to pre-service teachers.
Front. Psychol. 14:1139911.
doi: 10.3389/fpsyg.2023.1139911

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Prevalence of neuromyths among psychology students: small differences to pre-service teachers

Verena Novak-Geiger*

School of Education, University of Klagenfurt, Klagenfurt, Austria

Neuroscience will possibly aid the educational practice but neuromyths are prevalent worldwide. Certain misconceptions about learning, memory and the brain are prevalent in different groups and hard to dispel. Bridging the gap might be too far. However, Psychology may serve as a bridge between these distant fields. The present study examined neuromyth endorsement in psychology students. An online questionnaire based on 20 neuromyths and 20 neurofacts was used. Additionally, neuroscience exposure at university and media exposure was assessed. The sample consisted of psychology students (N=116) in Austria and was compared to a teacher-training sample. The different groups were compared using Signal Detection Theory, Chi-square test, non-parametric correlation analyses, and independent sample t-test. No correlation between neuroscience exposure at university and leisure time for psychology students at the beginning of their studies could be found. Here, the same misconceptions were among the most prevalent—compared to the teacher-training students sample. Results show significant difference between the groups on discrimination ability and response bias. Although psychology students share the same most prevalent misconceptions, they differ significantly in their amount of agreement. The reported study reveals a better discernment ability and lower response bias on neuromyths in the Psychology students' sample. On the individual item level, they performed better at rejecting some neuromyths than pre-service teachers. In conclusion, some neuroscience and pedagogical psychology training improves the ability to discriminate between true and false statements. Therefore, directly addressing these misconceptions within the study program—Teacher Training and Psychology—could reduce neuromyth endorsement.

KEYWORDS

neuromyths, psychology, teacher-training, SDT, prevalence, discrimination, response bias, misconceptions

1. Introduction

1.1. Neuromyths

As early as 2010, Neuroscience and Education have been announced as "An Ideal Partnership for producing Evidence-Based Solutions to Guide 21st Century Learning" (Carew and Magsamen, 2010, p. 685) and neuromyths (NM) as possible barriers. NM are defined as misconceptions about the human brain, learning, and memory processes (OECD, Organisation for Economic Co-operation and Development, 2007, p. 107–125) and have been investigated intensively over the last years and are widely believed within the educational field in Europe (Dekker et al., 2012; Grospietsch and Mayer, 2019; Krammer et al., 2019), the United States (Macdonald et al., 2017; van Dijk and Lane, 2020), Canada (Blanchette Sarrasin et al., 2019), Latin America (Gleichgerrcht et al., 2015), China (Zhang et al., 2019) and other countries (Janati Idrissi et al., 2020). The most prevalent and persistent misconceptions are (1) that individuals learn better when they receive information in their preferred learning style (Learning Styles), (2) that the absence of exposure to a rich learning environment by the age of 3 leads to a loss of learning capacities (Importance of 3 Years), and (3) that differences in hemispheric dominance can explain individual differences among learners (Hemispheric Dominance; Torrijos-Muelas et al., 2020). Although some claim that misconceptions are not relevant to their teaching practice, for example for award-winning teachers (Horvath et al., 2018) or university student's grades in the teacher training program (Krammer et al., 2021), others argue that they will "have serious consequences in the quality of education, as these beliefs pave the way for ill-grounded methodologies"(Ferrero et al., 2020, p. 2).

Different attempts have been made to explain the sources of neuromyths in recent years. For example, mass media (Zhang et al., 2019), outdated knowledge, and false interpretations with a kernel of truth (Grospietsch and Mayer, 2019) are responsible for the appearance of misconceptions. Additionally, certain cognitive biases, i.e.: confirmation bias—seem to be related to the belief in neuromyths (Rubin et al., 2022). For example, teachers believing in learning styles theory tend to discern and remember classroom situations as evidence that supports their view that learning information according to the individual preferred learning style aids understanding and remembering. Moreover, van Elk (2019) showed a relationship between neuromyths and a simple understanding of neuroscientific knowledge, a high need for cognitive closure, a fixed mindset, intuitive thinking, and in reverse scientific literacy. Considering science as static and unchanging and a need for unambiguous information predicted the belief in neuromyths. In other words, people who tend to form opinions relying on little information tend to believe in neuromyths. Similarly, people who rely on their intuition are expected to believe in neuromyths.

In addition to explaining the origin of neuromyths, several interventions to refute misconceptions have been investigated (Im et al., 2018; Lithander et al., 2021; Swire-Thompson et al., 2021) and different strategies have been used. On the one hand, no improvement in neuromyth belief could be found when taking a course in educational psychology (Im et al., 2018). Similarly, Macdonald et al. (2017) displayed that training in education or neuroscience results in a decrease but not a removal of false beliefs indicating that the gap between neuroscience and education might be too far. On the other hand, correcting neuromyths with refutation tasks was successful, also in the long term (Lithander et al., 2021).

To summarize, misconceptions about learning, memory, and the brain still exist in schools, among preservice and in-service teachers as well as headmasters. The knowledge about what practices deduced from notions of and statements about the brain are myths has not fully arrived in the educational setting yet. The high prevalence of neuromyths in the educational setting are a sign that the gap between neuroscience and education is wide and bridging this gap needs more interdisciplinary research (Thomas, 2019) and psychology could well aid as a link between neuroscience and education (Marsh et al., 2015; Wilcox et al., 2020) for two possible reasons. First, most psychology curricula include basic training in neuroscience and neurosciences are connected to topics covered in other psychological fields such as cognitive, social, or clinical neuroscience. Second, psychology alumni and alumnae are employed in different fields, as psychology is a multifaceted field. Students finishing their studies are engaged in clinical psychology, childcare, welfare institutions and as school psychologists—the belief in neuromyths may impede their professional practice. However, to the author's knowledge, no psychologists or students of psychology have been investigated on their neuromyth prevalence so far.

1.2. Signal detection theory

Answering a questionnaire on statements about learning, memory, and neuroscience with a right/wrong response scheme, forces participants to make a decision. Several aspects could affect humans' decisions (Grant et al., 2017). Hence, decisions are influenced by "(a) the prevalence of the characters[items] in the environment, (b) the expertise of the raters in detecting the characteristic, (c) the extent and direction of bias in their judgments, and (d) fluctuating levels of attention to the task (see Goldstein and Hogarth, 1997, […])" (Grant et al., 2017, p. 3). These influence the judgments' reliability. For example, there will be more rare or common facts or myths the participant encounters (prevalence), and the participant's expertise may vary (expertise), especially between different interest groups or professions. Furthermore, the participant's bias and whether the questionnaire is answered with or without distraction, in the morning or late in the evening (attention level) will influence the decision. The Hit Rate and the False Alarm Rate are included within these measures and both are affected by expertise and bias. SDT (Green and Swets, 1966) attempts to separate "a rater's ability from his or her response bias by defining a measure that reflects the *difference* between *Hit* and *False-Alarm Rates*" (Grant et al., 2017, p. 4). Accordingly, d' is the ability to differentiate between truth and absence thereof.

In SDT, stimuli presented as targets and correctly identified as such, are referred to as "Hits" and targets not identified as such as "Misses." Contrary, stimuli not presented as distractors and that are wrongly classified as targets are "False Alarms" whereas distractors not classified as targets are referred to as "Correct Rejections." For example, Pennycook and Rand (2021), applied SDT to individuals falling for fake news. Here, truth discernment is the degree of believed misinformation in relation to correct information and was calculated similarly to sensitivity (d′) in SDT: "belief in true news" minus "belief in false news." In their study, poor truth discernment relates to a deficit in careful reasoning, related knowledge, and the use of heuristics (familiarity and source). Similarly, SDT will be applied here, to assess how well participants can detect myths and facts in the current study. Therefore, the endorsement of neuromyths will be tested in a sample of psychology students, and the results will be compared to a sample of teacher-training students from a previous study (Krammer et al., 2019). The endorsement of myths and facts was defined as false alarms and hits, respectively. Similarly, denial of myths or facts was defined as correct rejections or misses. The SDT approach allows disentangling the ability to distinguish between true and false neuroscientific statements from a general response bias.

1.3. Hypothesis

Since information taught on neuroscience decreases but does not eliminate false beliefs about neuroscience, learning, and the brain (Macdonald et al., 2017; Rousseau, 2021) psychology students are expected to belief in neuromyths but show less neuromyth endorsement compared to teacher training students in Austria. Moreover, a difference in discrimination is expected because d' entails neuromyth endorsement represented by false alarms. Previous studies including participants with higher exposure to neuroscience revealed only small differences between the public and teachers (Macdonald et al., 2017) but did not use Signal Detection Theory. In their study, Macdonald et al. (2017) referred to people with many completed university or college courses related to the brain and neuroscience as a high-exposure group. Similarly, psychology students are exposed to neuroscience in university courses. Here, the teacher-training curriculum includes an introductory course to teaching and learning with a small amount of educational psychology. In this course, among the characteristics of the pedagogical profession, also educational science, psychological and sociological foundations of teaching and learning in relation to pedagogical fields of action are taught (Curriculum, 2019). Therefore, compared to psychology students this knowledge is introductory and not in-depth knowledge of the topic.

2. Materials and method

In order to answer the hypothesis on neuromyth belief in psychology students and their differences to teacher training students, a quantitative online survey was used.

The initial sample consisted of 120 mostly undergraduate psychology students. Four of them had to be excluded because of missing data after demographics. The mean age was 22.27 years ($SD = 4.77$) and, the vast majority were female students ($N = 83$), one-third male ($N = 32$), and one person "divers." All remaining participants were Bachelor Students of Psychology, with 81% in their first semester ($N = 95$). Most of the participants had A levels as their highest acquired educational degree ($N = 98$) whereas some already hold a bachelor's degree ($N = 13$). For a comparison of the present sample of psychology students with students in the educational field, the data from Krammer et al. (2019), made available at: https://osf.io/5tsfv/ (Krammer et al., 2019), was used with the permission of the first author. Here, 24 participants were excluded from the analysis due to missing data on age or semester, and a great number of missing values. Then, the final sample consisted of 648 students with a mean age of 20 ($SD = 3$), the vast majority in their first semester ($N = 613$) and being female participants ($N = 416$) compared to male participants ($N = 233$). Within this sample, no data on proficiency in neuroscience or exposure to neuroscience was collected.

The questionnaire used to investigate neuromyth endorsement was based on Dekker et al. (2012) and Krammer et al. (2019) containing 20 neuromyths and 20 neurofacts, demographic data, and neuroscience exposure either at university or in private were used. Participants were asked to report on attended lectures that included neuroscience or the brain as topics; on lectures or seminars primarily on neuroscientific topics and/or the brain; whether they attended related undergraduate introductory lectures and/or more advanced level courses within the curriculum. Moreover, they were questioned on their leisure time spent on topics such as brain and neuroscience and learning and memory. Additionally, two items were used for participants' self-rating on a 5-point scale (very bad, bad, medium, good, very good) for their neuro-knowledge and knowledge about learning and memory. In more detail, two questions to assess neuroscience exposure at university were included in the questionnaire: *Are or were the topics "neuroscience" or "brain" components of courses at the AAU that you attended?* and *Have you already taken one or more courses on the topic of learning?* The first employs a yes/no response option, and the second a three-point scale (none, one, several). Moreover, included were yes/no questions on the attendance of the introductory lecture and more advanced lecture in neuroscience (*Have you already attended the lecture Cognitive Neuroscience A?* and *Have you already attended the lecture Cognitive Neuroscience B?*) and questions on neuroscience exposure outside the university. One general question *(Do you spend your free time on topics related to the brain or neuroscience?)* and two questions on media exposure on a 4-point Likert Scale (never, seldom, sometimes often) were used (*Do you regularly watch shows on TV or streaming platforms that focus on neuroscience topics and the brain?; Do you regularly watch shows on TV or streaming platforms that focus on topics learning and memory?*).

The questionnaire was an online study using LimeSurvey Software and was sent to psychology students enrolled in a lecture at the end of their first semester via email by the lecturer. The attendees were able to participate in the waffling of a voucher and partial course credit.

Data was analyzed with IBM SPSS Statistics 28.0.0.0. Chi-square test for the effect sizes presented and Cramer's V (small effect ≤ 0.08; moderate effect ≤ 0.22; large effect ≥ 0.35) was used. Previous studies examining the underlying factor structure of neuromyths and neurofacts could not find a common factor for neuromyth items (Macdonald et al., 2017; Horvath et al., 2018; Krammer et al., 2019).

This study was carried out in accordance with the recommendations of the Institutional Review Board of the University of Klagenfurt with informed online consent from all subjects. The University of Klagenfurt Ethics Committee approved the study protocol. The ethics approval, study material, raw data and script is openly available at: https://osf.io/ndzwp/.

3. Results

The results section is structured as follows. First, I report neuroscience expertise in the psychology sample and the relationship with measured demographic variables and neuromyth acceptance and denial (frequencies, descriptive analyses, Spearman correlation) to answer whether neuroscience knowledge correlates with neuromyths denial and neuromyths acceptance. Next, I compare psychology students and teacher training students on the item level of the questionnaire (Proportions, Chi-square test, Cramer's V) to answer whether these groups differ in their neuromyth endorsement. Finally, I describe the results of the comparison of discrimination ability and response bias of and between the groups (SDT analysis, independent sample *t*-test) to compare psychology and teacher-training students.

3.1. Neuroscience expertise

Descriptive data analysis indicate that psychology students are not immune to misconceptions about learning and the brain although exposed to neuroscience through lectures and leisure activities. Among psychology students, 95% ($N = 110$) stated, that neuroscience or the brain were topics in courses they attended so far, and 87% ($N = 101$) attended an introductory lecture but only 7% ($N = 9$) attended an advanced lecture on cognitive neuroscience. Regarding neuroscience exposure outside university, 46% ($N = 53$) were not concerned with this topic in their free time compared to 53% ($N = 62$) with some exposure, and 1% ($N = 1$) reported high exposure. Within the psychology students sample, media exposure related to neuroscience and the brain was 31% ($N = 36$) never, 56% ($N = 65$) seldom, and 12% ($N = 14$) sometimes and 1% ($N = 1$) often. Additionally, media exposure related to learning and memory was 32% ($N = 37$) never, 49% ($N = 57$) seldom, 17% ($N = 20$) sometimes and 2% ($N = 2$) often. Participants' self-rating for their neuro-knowledge was 5% ($N = 6$) very bad, 47% ($N = 54$) bad, 45% ($N = 52$) medium and 3% ($N = 4$) good. Participants' self-rating of their knowledge about learning and memory was 2% ($N = 2$) very bad, 31% ($N = 36$) bad, 56% ($N = 65$) medium and 11% ($N = 13$) as good.

The prevalence of misconceptions about learning and the brain in the psychology student sample compares to previous studies with teachers, headmasters, and teacher training students' samples. Table 1 displays the response proportions (percentage) and statistics for each item. Among the psychology students sample the highest false alarms are seen with *NM9 "Students learn better when information is presented according to their learning type"* (91%) followed by *NM15 "Short-term coordination exercises help to better integrate the left and right hemisphere"* with 67 percent wrong agreement with the statement. The third was 64% *NM18 Lessons should be designed in such a way that both sides of the brain are addressed*. The highest proportion of correct rejections (Neuromyths classified as "wrong") received items *NM16* "*The brain is not active when we sleep.*" (97%), and Item *NM13* "*Intelligence is inherited and not changeable by the environment*" (85%). Almost half of the participants (47%) were uncertain about the classification and chose "do not know" as an answer on *NM3* "*It is scientifically proven that fatty acid (omega-2, omega-6) containing food supplements have a positive effect on academic success.*" as well as on item *NM12* "*Body-eye coordination exercises can positively affect reading ability.*" (41%) and *NM10* "*Sensory-rich environments improve brain development in kindergarten children.*" (37%).

The distributions of the frequencies for neuromyth denial, neuromyth acceptance, neurofacts denial and neurofacts acceptance were not normal as indicated by Kolmogorov–Smirnov and Shapiro–Wilk tests ($p < 0.001$ and $p >= 0.052$). As a result, non-parametric Spearman Correlations were used.

Spearman correlation analysis on demographic variables in the psychology students' sub-sample were computed and are displayed in Table 1. No significant correlation between neuromyth consent and demographic variables as well as neurofact consent and demographic variables could be found. However, neuromyth consent showed a small significant correlation with neurofact consent ($r = 0.26$, $p < 0.005$), a medium negative significant correlation with d prime ($r = -0.575$, $p < 0.001$), a medium negative correlation with response bias c ($r = -0.438$, $p < 0.001$). Neuromyth rejection showed medium significant correlation with neurofact rejection ($r = 0.556$, $p < 0.001$). Neuromyth rejection showed a high correlation with response bias ($r = 0.718$, $p < 0.001$). Additionally, neurofact consent (correctly accepting neurofacts) showed a small negative correlation with neurofact rejection ($r = -0.272$, $p < 0.005$), a small correlation with

TABLE 1 Spearman correlations among measured variables in psychology student's sample.

	1	2	3	4	5	6	7	8	9	10	11	12	13	14
1. NM consent	–													
2. NM rejection	**−0.219**	–												
3. NF consent	**0.265****	0.043	–											
4. NF rejection	0.116	**0.556****	**−0.272***	–										
5. Discrimination (d′)	**−0.575****	0.011	**0.365****	**−0.726****	–									
6. Response bias (c)	**0.438****	**0.718****	**−0.408****	**−0.794****	−0.278	–								
7. Lecture A	0.079	0.094	−0.008	−0.078	0.033	−0.066	–							
8. Lecture B	0.062	−0.046	−0.135	−0.004	−0.072	0.051	0.126	–						
9. Course Topic	0.162	−0.051	−0.157	−0.065	−0.103	−0.095	**0.491****	0.076	–					
10. TV neuro	0.056	0.029	−0.080	0.124	−0.180	0.103	−0.159	0.076	0.136	–				
11. TV memory	0.077	0.028	−0.115	0.119	−0.177	0.068	−0.025	0.005	0.204	**0.540****	–			
12. Self-rating neuro	0.081	0.050	0.017	0.089	−0.115	0.084	**−0.208**	−0.092	0.117	**0.270***	0.184	–		
13. Self-rating memory	0.174	0.016	0.028	−0.009	−0.063	0.047	0.105	−0.156	**0.299****	0.263*	0.163	**0.471****	–	
14. Leisure	0.123	−0.0	−0.004	−0.029	−0.086	0.045	0.003	0.074	0.062	**0.385****	**0.318****	**0.264**	0.166	–

Significant correlations are printed in bold; *$p \leq 0.005$; **$p \leq 0.001$.

neuromyth consent ($r = 0.265$, $p < 0.005$) as well as a small negative correlation with neurofact rejection ($r = -0.272$, $p < 0.005$). Moreover, neurofact rejection showed a medium correlation with neuromyth denial ($r = 0.556$, $p < 0.001$) and a small negative correlation with neurofact consent ($r = -0.272$, $p < 0.005$).

Participants' self-rating on their neuroscientific knowledge showed a small significant correlation with *leisure* ($r = 0.26$, $p = 0.004$), and a medium significant correlation with their self-rated knowledge on memory and learning ($r = 0.47$, $p < 0.001$). Additionally, a small correlation between self-rated neuro-knowledge and watching broadcasts or documentaries depicting neuroscientific topics ($r = 0.27$, $p = 0.003$). Participants' self-rating on their knowledge on memory and learning showed the higher the self-rated knowledge on the topic memory and learning, the more courses that depicted the topics were attended ($r = 0.30$, $p < 0.001$).

3.2. Item-level comparison for psychology students and teacher-training students

The teacher training students sample shares the first three most prevalent misconceptions in place with the psychology students sample: *NM9* "*Students learn better, when information is presented according to their learning type Coordination exercises help to better integrate hemispheres*" (97%), *NM15* "*Short-term coordination exercises help to better integrate the left and right hemisphere*" (88%) and *NM18* "*Lessons should be designed in such a way that both sides of the brain are addressed.*" (86%) were the most prevalent Neuromyths among pre-service teachers. Moreover, *NM5* "*Brain dominance (left/right) explains individual learning differences.*" (82%) and *NM12* "*Body-eye coordination exercises can positively affect reading ability.*"(80%) were believed by the vast majority of the teacher training sample. Similar to the psychology students. The highest proportions of correct rejections of neuromyth items among the teacher-training sample received item *NM16* "*The brain is not active when we sleep.* "(95%).

A 2 (background: psychology, teacher-training) × 3 (response to item: correct, incorrect, do not know) Chi-square analysis ($df = 2$) on the responses of the neuromyth items between psychology students and teacher training students is displayed in Table 2 and revealed that 15 of the 20 items differed significantly in their response patterns. The effect sizes of five neuromyth items were small (*NM 11*, *NM, 13*, *NM16*, *NM 19*, and *NM 20*) whereas the effect sizes for the remaining 15 items were moderate. The highest effect size could be found for four items *NM4*, *NM5*, and *NM12* and *NM18*. Psychology students were less likely to agree on the neuromyth *NM5* that "*Brain dominance (left/right) explains individual learning differences*" compared to teacher training students (54 vs. 82%, effect size Cramer's V 0.304) as well as on neuromyth *NM4* "*We only use 10% of our brain*" (15 vs. 44%, effect size Cramer's V 0.285). Moreover, neuromyth *NM12* "Body-eye coordination exercises can positively affect reading ability." was less believed by psychology students (41%) compared to teacher training students (80%) with an effect size of Cramer's V 0.275. Here, psychology students used the "do not know" category more often (41%) compared to teacher training students (16%). *NM18* "*Lessons should be designed in such a way that both sides of the brain are addressed*" was less believed in the psychology students sample compared to teacher training students (64 vs. 86%, effect size Cramer's V 0.244). Additionally, Psychology students were better at rejecting *NM15* "*Short-term coordination exercises help to better integrate the left and right hemisphere*" compared to teacher training students (67 vs. 88%, effect size Cramer's V 0.222). However, psychology students chose "do not know" more often than teacher-training students.

3.3. Discrimination ability and response bias

Next, the ability to discriminate myth and fact in neuroscience statements was tested between the two samples using SDT. Right (R) and wrong (W) answer categories were included, and do not know (DK) were excluded from the analysis. Hit and false alarm rates (endorsements of neurofacts versus neuromyths) were computed individually, as were discrimination ability d' and response bias c (see Macmillan and Creelman, 2005). Bias c values of zero reflect unbiased, neutral responding. In the present setting, positive values of bias c reflect the conservative tendency to rather endorse statements as false and negative values reflect liberal responding and the tendency to endorse statements as true.

In the psychology sample, the mean hit rate was $M = 12.1$ ($SD = 2.8$), and the mean false alarm rate was $M = 6.7$ (SD = 2.6). The mean hit and false alarm rates in the teacher training sample were $M = 12.3$ ($SD = 2.6$) and $M = 8.5$ ($SD = 2.2$). Distributions of d′ and response bias c for both groups are shown in Figure 1. An independent samples *t*-test on the ability to discriminate (d′) and the response bias (c) was conducted on the two samples. Discrimination ability d' was significantly higher for psychology than for teacher training students ($M = 0.99$, [$SD = 0.57$], $M = 0.74$ [$SD = 0.49$]; $t(145.905) = -4.540$, $p < 0.001$, $d = 0.51$). Similarly, response bias c was significantly smaller for psychology than for teacher training students ($M = -0.31$, [$SD = 0.36$], $M = –46$, [$SD = 0.28$]; $t(139.322) = -0.437$, $p < 0.001$, $d = 0.53$). Discrimination ability and response bias are displayed in boxplots in Figures 1A,B for both samples.

Moreover, correlations of variables with discrimination ability d' and response bias c are shown in Table 1. Here, Neurofact consent showed a small correlation with discrimination ability d prime ($r = 0.365$, $p < 0.001$) and a similar but negative correlation with response bias ($r = -0.408$, $p < 0.001$). Neurofact rejection showed a high negative significant correlation with d prime ($r = -0.726$, $p < 0.001$) and response bias c ($r = 0.794$, $p < 0.001$).

4. Discussion

In the present study, descriptive data analysis indicate that psychology students are not immune to misconceptions about learning and the brain—though they are to some extent trained in neuroscience. Here, the most prevalent misconceptions were (1) *Learning styles*, (2) "*Short-term coordination exercises help to better integrate the left and the right hemisphere*" and (3) the notion that "*Lessons should be designed in such a way that both sides of the brain are addressed.*" In the Austrian pre-service teacher sample by Krammer et al. (2019), the same neuromyths showed the highest prevalence. These groups were then compared.

A difference on the individual item level on some questions could be shown. The largest significant difference was discovered for the item "*Brain dominance (left/right) explains individual learning differences.*": Psychology students were less likely to accept this statement as correct. Similarly, they were more likely to identify "*We only use 10% of our*

TABLE 2 Percentage of responses between psychology students and teacher training students on each neuromyth item, together with item-level Chi2 test statistics (all *df*=2).

Neuromyths	Psychology students			Teacher training students					
	R	W	DK	R	W	DK	Chi^2	*p*	Cramer's *V*
(NM1) The first language must be acquired before the second language is acquired completely.	19(23)	63(71)	18(22)	35(233)	54(361)	11(77)	12.15	**0.002**	0.124
(NM2) When students do not drink enough water (6–8 glasses), their brains shrink.	13(13)	63(73)	24(31)	5(32)	75(502)	20(137)	10.90	**0.001**	0.117
(NM3) It is scientifically proven that fatty acids (omega-2, omega-6) containing food supplements have a positive effect on academic success.	25(29)	28(33)	**47(54)**	38(255)	16(107)	**46(311)**	13.35	**0.001**	0.130
(NM4) We only use 10% of our brain.	15(17)	78(90)	8(9)	44(294)	38(253)	18(123)	63.89	**<0.001**	**0.285**
(NM5) Brain dominance (left/right) explains individual learning differences.	**54(63)**	20(23)	26(30)	**82(552)**	3(18)	15(101)	72.64	**<0.001**	0.**304**
(NM6) The brains of boys and girls develop at the same rate.	31(35)	45(53)	24(28)	19(125)	55(366)	26(175)	8.04	**0.018**	0.101
(NM7) Brain development is completed between the ages of 11 and 12.	3(4)	81(93)	16(19)	4(25)	67(446)	30(198)	8.896	0.**012**	0.106
(NM8) In childhood, there are critical phases, after which certain things can no longer be learned.	38(44)	43(50)	19(22)	51(340)	29(197)	20(135)	9.318	0.**009**	0.109
(NM9) Students learn better when information is presented according to their learning type.	**91(107)**	6(7)	3(3)	**97(654)**	1(6)	2(12)	16.343	**<0.001**	0.144
(NM10) Sensory-rich environments improve brain development in kindergarten children.	38(46)	25(27)	**37(44)**	57(383)	15(104)	28(186)	12.577	**0.002**	0.126
(NM11) Children are less receptive after consuming sugary snacks and/or drinks.	40(46)	27(31)	33(39)	39(262)	35(263)	26(174)	4.254	0.119	0.073
(NM12) Body-eye coordination exercises can positively affect reading ability.	47(54)	12(14)	**41(48)**	**80(536)**	4(24)	16(111)	59.624	**<0.001**	**0.275**
(NM13) Intelligence is inherited and not changeable by the environment.	10(11)	**85(98)**	5(6)	7(46)	**85(570)**	8(55)	2.118	0.347	0.052
(NM14) Learning difficulties related to developmental differences in brain function cannot be corrected by education.	33(39)	39(45)	28(33)	19(127)	47(319)	**34(225)**	12.457	**0.002**	0.126

(Continued)

TABLE 2 (Continued)

Neuromyths	Psychology students			Teacher training students					
	R	W	DK	R	W	DK	Chi²	*p*	Cramer's *V*
(NM15) Short-term coordination exercises help to better integrate the left and right hemispheres.	**67(78)**	9(10)	24(29)	**88(593)**	4(29)	7(50)	36.010	**<0.001**	**0.222**
(NM16) The brain is not active when we sleep.	1(1)	**97(113)**	2(2)	1(9)	**95(673)**	4(24)	1.269	0.530	0.040
(NM17) There is not just one but several independent intelligences localized in different brain regions.	50(58)	19(22)	30(35)	61(408)	7(50)	**32(212)**	16.423	**<0.001**	0.145
(NM18) Lessons should be designed in such a way that both sides of the brain are addressed.	**64(75)**	14(16)	22(26)	**86(575)**	2(15)	12(82)	46.829	**<0.001**	**0.244**
(NM19) Going to school for several years makes children less creative. Children are most creative before entering school.	33(38)	35(41)	32(37)	43(287)	31(210)	26(174)	4.222	0.121	0.073
(NM20) Highly gifted people do not need to learn to perform well in school.	4(5)	**89(103)**	7(9)	5(33)	**87(585)**	8(53)	0.99	0.951	0.011

R, W, DK refer to the response codes right, wrong, do not know. Numbers printed in bold highlight similarities or differences between the group's responses.

brain" as incorrect and did not accept "*Body eye coordination exercises can positively affect reading ability*" as often as teacher-training students as a true statement. The groups answered differently on "*Lessons should be designed in such a way, that both sides of the brain are addressed.*" and "*Short-term coordination exercises help to better integrate the left and right hemisphere.*" Again, psychology students were less likely to accept these statements as true. The group differences on individual items could have three different causes. First, the statements about brain dominance and on designed lessons addressing both sides of the brain can be attributed to the distinction in the student's desired profession and the resulting study content. Prospective teachers are more concerned with learning and differentiated teaching than psychology students are. Psychology is the study of the human psyche and behavior. Second, psychology students used the answer category "do not know" more often for some of those items (*Body eye coordination exercises can positively affect reading ability; Short-term coordination exercises help to better integrate the left and right hemisphere*). Here, the lower self-rating of neuroscientific knowledge these students reported and/or the notion of the complexity of the human brain after attending the introductory lecture on cognitive neuroscience could be a possible cause. Third, the vast majority of the psychology students correctly classified the statement "*We only use 10% of our brain*" as wrong, compared to teacher training students. Again, more (introductory) knowledge on the brain may serve as a reason. For teacher-training students, addressing neuromyths in lectures and courses could improve the belief in neuromyths.

Psychology students' self-rating on their neuroscientific knowledge showed a correlation with leisure—time spent on neuroscientific topics in the free time. Moreover, participants' self-rating of their knowledge of memory and learning is connected to the amount of time spent watching documentaries and broadcasts related to learning, and memory. Participants self-rating on neuroscience and learning and memory are related as well. Attended introductory lecture on neuroscience and/or advanced lecture on neuroscience showed no correlation with neuromyth consent or denial and no correlation with deeprime discrimination ability and response bias. University courses depicting the topic of neuroscience, learning and memory showed a small correlation with participants' self-rating memory and learning. They might feel more confident due to the gained knowledge. No significant correlation of demographic variables with neuromyth belief or denial, neurofact acceptance or denial was found. Here, the demographic However, this data was not available for the compared teacher-training students.

The initial hypothesis predicted that psychology students do not differ significantly in their prevalence of neuromyths to teacher-training students in Austria because the amount of neuroscience exposure is not sufficient to make a difference in the prevalence. Firstly, the survey responses depict a similar picture of the most prevalent statements in both samples. Although the same misconceptions are most prevalent in both samples, psychology students' neuromyth acceptance (false alarms) differs significantly from the teacher-training students. Initial training in neuroscience and in topics related to learning and memory makes a difference in the percentage of neuromyth endorsement for individual items. Future teachers' attention should be drawn to the complexity of the human brain and difficulty in formulating (simple) recommendations for lessons. Moreover, more knowledge about neuroscience would be a protective factor.

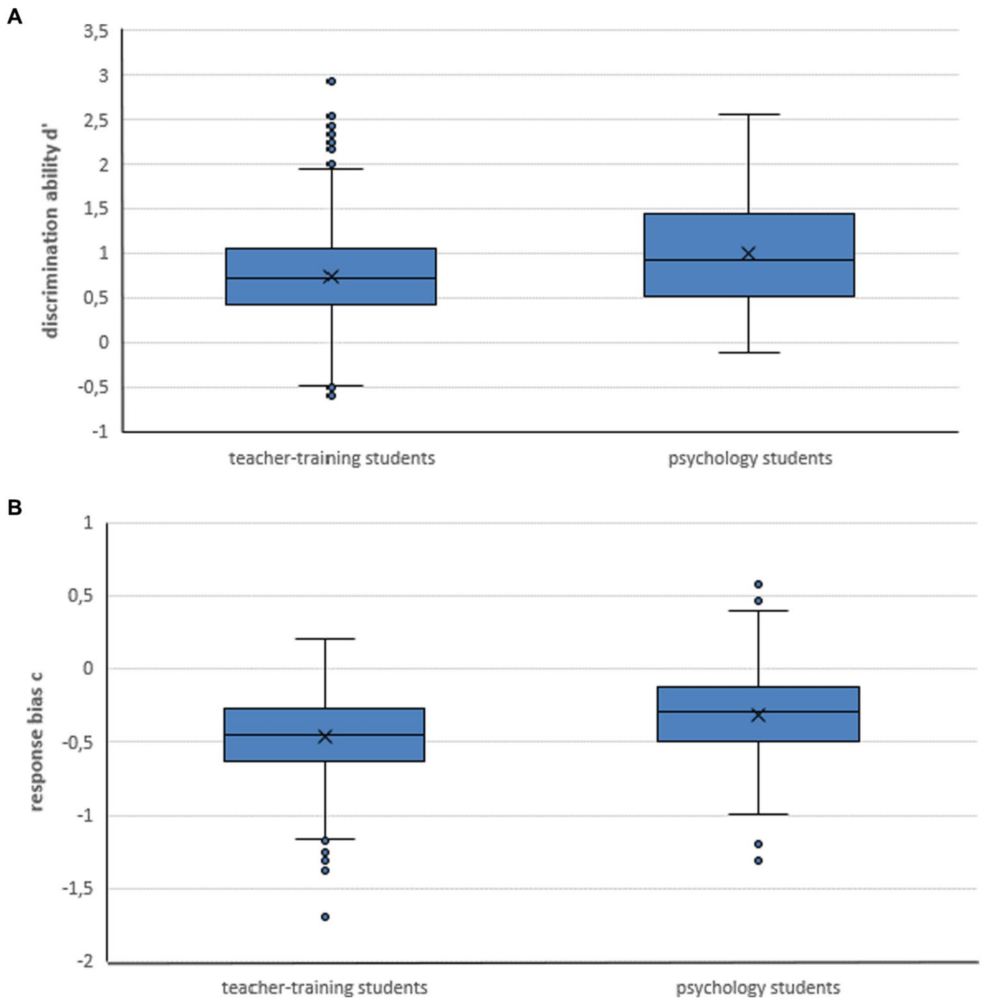

FIGURE 1
Boxplots of discrimination ability d′ **(A)** and response bias c **(B)** in the neuromyth questionnaire for the psychology and teacher training samples; crosses reflect means.

Additionally, a SDT analysis revealed that both groups were similar in their percent of correct answers on neurofacts, and discrimination ability was different as well as response bias. Moreover, an independent sample *t*-test on these measures revealed significant difference between psychology students and pre-service teachers. Psychology students showed a higher discrimination ability and were therefore better at distinguishing between correct and incorrect statements.

However, the present study faces certain limitations. The items used in the questionnaire need development, as Sullivan et al. (2021) suggested. Some statements cannot be clearly classified into myth or fact because the evidence is ambiguous. Moreover, precise reading is essential to recognize the difference between fact and fiction in some items (for example, critical period vs. sensible period in childhood). Another improvement could be achieved in statements with more context information in contrast to one-sentence statements. Additionally, the teacher-training student sample does not contain demographics on neuroscience exposure, making a comparison difficult.

Within education, Learning Styles are not seen as a holistic concept. Confusion with theories of learning is sometimes understood as Visual–Auditory-Reading-Kinaesthtik (VARK; Fleming and Mills, 1992) framework, and sometimes as multiple intelligences by Gardner. Additionally, they find their entry into teaching via techniques (Papadatou-Pastou et al., 2021). Although instruction based on learning styles does not result in an improvement in learning (Rogowsky et al., 2020) the concept is still being used [for example in Çam et al. (2022)]. Future research could aim at examining the different understandings of learning styles, as this neuromyth received the highest amount of wrong answers. Similarly, psychology students may not use the same concept of learning styles. Here, qualitative research could be employed. These studies could use qualitative approaches or experimental approaches to gain a deeper understanding of people's understanding of neuromyths, their knowledge, and their application. Qualitative research may address individual neuromyths, for example, the most prevalent misconception on learning styles. Additionally, future research may focus on the question of whether graduated psychology students have gained knowledge that protects against the belief in neuromyths, how this knowledge develops, and if the proportion of correct answers on the misconceptions and facts about learning, memory and the brain changes.

Furthermore, the dissemination of misconceptions in schools and at the tertiary level can be suspended even though knowledge in neuroscience not directly coincides with neuromyth denial. As recently shown by Ruiz-Martin et al. (2022), interventions with in-service teachers resulted in a reduction of Neuromyths. Moreover, addressing these misconceptions directly within the curriculum could result in an improvement. Therefore, strategies to encounter misinformation, as described by Ecker et al. (2022) could be used. "Intervention approaches that focus on both activating rational thinking (i.e., refutation-based interventions) and mitigating intuitive thinking, as well as non-prescriptive approaches like teacher professional development workshops and seminars on the neuroscience of learning, are promising avenues to dispel beliefs in neuromyths and to instill evidence-based teaching practices in the classroom, respectively." (Rousseau, 2021, p. 9).

Data availability statement

The datasets presented in this study can be found in online repositories. The names of the repository/repositories and accession number(s) can be found at: https://osf.io/ndzwp/.

Ethics statement

The studies involving human participants were reviewed and approved by Institutional Review Board of the University of Klagenfurt. The participants provided their written informed consent to participate in this study.

Author contributions

The author confirms being the sole contributor of this work and has approved it for publication.

Funding

The study was partly funded by the School of Education, University of Klagenfurt, Klagenfurt, Austria.

Acknowledgments

This paper and the research behind it would not have been possible without the exceptional support of my supervisor, Bartosz Gula. I also express my gratitude to my colleague, Martin Wieser, for his helpful comments in the process.

Conflict of interest

The author declares 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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frontiers | Frontiers in Psychology

TYPE Original Research
PUBLISHED 19 June 2023
DOI 10.3389/fpsyg.2023.1136246

Check for updates

OPEN ACCESS

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Greece

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Hui Luan,
National Taiwan Normal University,
Taiwan
Yunus Doğan,
Firat University,
Türkiye

*CORRESPONDENCE
Fauziah Sulaiman
✉ fauziahs@ums.edu.my

SPECIALTY SECTION
This article was submitted to
Educational Psychology,
a section of the journal
Frontiers in Psychology

RECEIVED 02 January 2023
ACCEPTED 14 March 2023
PUBLISHED 19 June 2023

CITATION
Uden L, Sulaiman F, Ching GS and Rosales JJ Jr (2023) Integrated science, technology, engineering, and mathematics project-based learning for physics learning from neuroscience perspectives.
Front. Psychol. 14:1136246.
doi: 10.3389/fpsyg.2023.1136246

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Integrated science, technology, engineering, and mathematics project-based learning for physics learning from neuroscience perspectives

Lorna Uden[1], Fauziah Sulaiman[2]*, Gregory S. Ching[3] and Jeffry Juan Rosales Jr.[3]

[1]School of Computing, Faculty of Computing and Digital Technologies, Staffordshire University, Stoke-on-Trent, United Kingdom, [2]Faculty of Science and Natural Resources, Universiti Malaysia Sabah, Kota Kinabalu, Sabah, Malaysia, [3]Graduate Institute of Educational Administration and Policy, National ChengChi University, New Taipei, Taiwan

For many students, learning physics is difficult because of its abstractness. To help students to learn physics, we have developed the Integrated Science, Technology, Engineering, and Mathematics Projects Based Learning (STEM-PjBL) method based on principles from neuroscience. We believe that incorporating principles from educational neuroscience would help students learn better. This paper describes our experiments of implementing the integrated STEM-PjBL Module in physics, i.e., classical mechanics, to secondary school students in Malaysia and South Korea. The study consists of two groups of students: the experiment group, 77 in total, comprising those who have undergone the integrated STEM-PjBL, and the control group, again 77 in total, who experienced the traditional approach. The Colorado Learning Attitudes Science Survey (CLASS) was conducted for the two groups on students' beliefs about physics and learning physics before and after the implementation. The paired sample *t*-test from the pre-survey and post-survey shows that the integrated STEM-PjBL group has a more positive shift in belief about physics and learning physics than the traditional group. The results of the independent samples *t*-test for students' beliefs about physics and learning physics, compared with the post-survey between the experimental group and the traditional group for both Malaysian and Korean perspectives, show that the experimental group has a higher mean compared to the traditional group. This paper explains why the integrated STEM-PjBL has improved students' beliefs about physics and learning physics, from the neuroscience education perspective. Finally, the paper concludes with guidelines for teachers who wish to implement the integrated STEM-PjBL in the classroom.

KEYWORDS

integrated STEM-PjBL, students' beliefs, physics, learning physics, educational neuroscience, framework

1. Introduction

Physics is a complex subject to learn (Veronika et al., 2017). Students often have this perception, and they also have low confidence in learning physics, resulting in fewer students taking up physics at school (Fatin et al., 2012). According to Dolin's study (as cited in Angell et al., 2004), learning physics requires students to learn many types of representation, such as experiments, graphs, and mathematical symbols. Students must understand and learn the transformation between all these representations. Another factor that hinders students from studying Physics is that they are not interested in the subject and feel bored (Hirschfeld, 2012). As a result, most students only managed to obtain an average grade in physics (MoE, 2013–2025; Halim et al., 2018). Factors like lack of teachers' engagement, lack of class activities that promote learning, teachers' overload of work that only focuses on finishing the syllabus within the time frame given, and teachers who are not self-confident in teaching practical physics work are the reasons why students stay away from physics. Besides, students' poor attitudes and no interest toward physics are also factors that contribute to this issue (Josiah, 2013). Most students think physics is boring, difficult, and irrelevant to daily life (Williams et al., 2003). Lack of laboratory facilities and less exposure to practical instruction led to poor achievement of physics in school (Daramola, as cited in Musasia et al., 2012). Teachers also lack exposure to science process skills to carry out activities in class (Rose et al., 2013). Although many realize the importance of physics in school, the teaching and learning of physics is still a great concern in education.

Most students who learn physics for the first-time result in negative shifts in beliefs about physics and learning physics (Madsen et al., 2015). Students with negative beliefs would consider physics to be difficult (Sahin, 2010) and beyond their capabilities to comprehend (Kovanen, 2011). The difficulty in learning physics results in declining enrolment in physics by students in the secondary school (Wang et al., 2017; Sheldrake et al., 2019). Physics instruction is a crucial factor that affects the shift in students' beliefs about physics and learning physics (Hammer, 1994; Wieman and Perkins, 2005; Madsen et al., 2015). Students who had negative experience are associated with unengaging instruction (Wang et al., 2017). Research has shown that traditional instruction resulted in a negative experience for students when learning physics (Donley and Ashcraft, 1992; Sahin, 2010; Madsen et al., 2015; Hairan et al., 2018). Beliefs about physics and learning physics significantly impact how students' approach and learn physics (Hammer, 1994; Chang, 2005; Mistades, 2007), and these attitudes are crucial when students first encountered physics. Students who hold positive beliefs about physics and learning physics tend to believe that physics knowledge is a coherent and logical method to understand the world (Madsen et al., 2015). Therefore, identify students' belief in physics is crucial before mentioning their interests, attitudes, engagement, and motivation.

Research-based instruction with an explicit focus on inquiry, modeling building instruction, experimentation and real-world contexts result in a positive experience for students in physics and learning physics (Madsen et al., 2015). It is our belief that integrated STEM-PjBL physics teaching could be used to improve students' beliefs about physics and learning physics. Research has been done regarding the acceptance of learning physics, e.g., students' interest decreased in learning physics at secondary school (O'Neill and Mcloughlin, 2021), students' preferences for learning physics at the college level declined (Riskawati and Marisda, 2022); students' beliefs toward learning physics and its influencing factors, i.e., students' beliefs to learn physics, students attitudes toward physics, and influence of cultural belief on students to learn physics (Chala et al., 2020). Researchers suggested that teachers should change their way of teaching physics and learning style to boost students' interest at the secondary level (Ziad et al., 2021). However, as far as we know, there has been no research carried out to discuss the shift in belief about physics and learning physics, particularly from the neuroscience perspective.

The aim of this study was to investigate the effectiveness of integrated STEM-PjBL physics method to help students to improve their beliefs about physics and learning physics among Malaysian and Korean students. The objectives of the study are:

(1) To investigate the effectiveness of integrated STEM-PjBL physics method to improve students' beliefs about physics and learning physics.
(2) To compare beliefs about physics and learning physics between Malaysian students and Korean students after the implementation of integrated STEM-PjBL physics module.
(3) To discuss the findings from the principles of educational neuroscience.

Educators and schools around the world are increasingly using the knowledge, techniques, and programs developed from a new understanding of how our brains learn; that is neuroscience in their classrooms. Educational neurosciences empower teachers with a new understanding about how students learn. Principles from educational neuroscience have important implications to understanding learning. In our research we have incorporated the principles of neuroscience in our STEM-PjBL to teach physics and explain why it was successful. Based on the research findings from our study, guidelines based on educational neuroscience will be provided to guide teachers how to design effective STEM-PjBL.

This paper begins with a brief review of teaching and learning and why we proposed STEM-PjBL. A brief overview of Project Based Learning for STEM and neuroscience and their implications for teaching and learning are given. This is followed by description of the case study and methodology. Subsequent sections present the results. This is followed by discussion and guidelines to design STEM-PjBL based on principles from neuroscience. The paper concludes with the conclusion and recommendations for further studies.

2. Literature review

Physics is well-known as a driving force for innovation and the development of new technologies (Lee and Kim, 2018). This is because physics has a strong connection to the integrated STEM elements (Bunyamin et al., 2020). To ensure students have a good understanding of physics, they must have a strong foundation in understanding classical mechanics concepts, which are taught starting in secondary education (Hairan et al., 2018). Students who understand classical mechanics concepts are known to have positive beliefs about physics and learning (Kiong and Sulaiman, 2010; Sahin, 2010; Madsen et al., 2015). Applying appealing physics instruction to students can help students to understand classical mechanics concepts better (Aviyanti, 2020), experience a positive shift in beliefs about physics and learning physics as well as having a personal interest, sense making and effort, real world connections, conceptual connections, applied conceptual understanding, problem solving in general, problem solving confidence and problem solving sophistication (Adams et al., 2006) and resulting in having a desire to pursue STEM majors and careers (Wang et al., 2017).

2.1. Ways to teach physics

The ways of teaching physics have been evolving for almost 200 years. There are many approaches educators, teachers, and lecturers use to teach physics across levels, e.g., through experiments and collaborative learning in physics (Reiner, 1998), through a contextual approach (Wilkinson, 1999), and real-life context for learning physics (1999). Entering the millennial, more approaches were introduced, including; problem-based learning through online (Atan et al., 2005), active learning strategy (Karamustafaoglu, 2009), teaching physics using PhET simulations (Wieman, 2010), using analogies and examples to overcome misconceptions in physics (Brown, 2014), individual and group learning in physics (Bocaneala, 2015), project-based learning to teach pre-service teachers (Olzan and Bevins, 2016), teaching physics trough practical work (Lee and Fauziah, 2018), teaching physics using history (Karam and Lima, 2022); use of anecdotes to show how physics works (Parmar, 2022) and many more. To promote the interest of students learning, a new approach is needed to meet with the demand of today's employers' needs.

2.2. A new approach to learn physics

Employers nowadays are demanding thinking, communication, team, and problem-solving skills. Few of these skills are evident in classroom teaching, with students memorizing facts for regurgitation. Traditional teaching is typically characterized by students sitting passively in the classroom as receivers of information, and the teacher is the sole information giver. There is no interaction between students and teachers. Teaching is typically textbook-driven, and information is often presented as discrete parts. The role of the teacher is to transmit information to the passive students. This approach creates many problems. Firstly, students regurgitate what they have learned without understanding. Secondly, students often perceive what they have learned as detached from the real world (Uden and Beaumont, 2006). Thirdly, there is no interaction between the teacher and other students. Fourthly, students rely on the teacher to tell them what to think and learn. Fifthly, students merely learn content without problem-solving skills.

To meet the demand of employers for graduates possessing the problem-solving, communication, critical thinking, team working and self-directed learning skills, there is an urgent need to change the way we teach. This is particularly important for the teaching of physics to students. Physics is a very abstract subject. Students find it hard to learn because of its abstractness. Project-based learning is an alternative approach to teaching and learning that would enable students to acquire the skills they needed in life and those demanded by employers.

2.3. The integrated STEM-PjBL

There are several studies in the literature reporting different aspects of project-based learning (PjBL) pedagogy, for instance, PjBL for in-service teachers development to provide effective teachers instruction (Holubova, 2008); PjBL to analyze student cognitive achievement in learning physics (Santyasa et al., 2020); examine the impact of PjBL games on students' physics achievement in physics (Baran et al., 2018); Integrating PjBL with E-Learning through lesson study activities to improved student quality of learning (Widyaningsih and Yusuf, 2020) and PjBL on self-efficacy among high-school physics students (Samsudin et al., 2017). However, the effect of STEM-PjBL implementation on students' belief in physics and learning physics at the high school level still needs proof.

PjBL is an instructional methodology based on the constructivist learning theory, in which students learn important skills by doing actual projects (Holubova, 2008). Solving authentic problems in real-world situations is a crucial activity where students apply core academic skills and creativity. Final products such as videos, artwork, reports, photography, music, model construction, live performances, action plans, digital stories, and websites are examples of PjBL artifacts. Normally, they executed the projects using a wide range of tools. On the other hand, STEM education is based on educating students in four specific disciplines, i.e., science, technology, engineering and mathematics into a cohesive learning paradigm based on real-world applications (Sumintono, 2015). Many countries accept STEM education because it provides opportunities to equip students with the knowledge and skills needed in the 21st century and to cope with the challenges of the fourth industrial revolution (Naudé, 2017; Suraya et al., 2017; Brown-Martin, 2018; Türk et al., 2018). For example, Malaysia adopted STEM education by introducing the Malaysian Education Blueprint (2013–2015) in 2013 that aims to raise the existing standard of science and technology education (Bakar et al., 2019). The blueprint introduction is the continuous effort to empower Malaysia to become a developed nation with a STEM-literate society, achieve a targeted highly skilled, qualified STEM workforce and meet the demands of a STEM-driven economy (Shahali et al., 2017). In Korea, the Science, Technology, Engineering, Art and Mathematics (STEAM) STEAM education policy was issued nationwide in 2011 by the Ministry of Education in Korea purposely to promote STEAM education in primary and secondary schools (Kang, 2019). The main goal of STEAM education in Korea is to produce students with the ability to create new ideas or products formed by STEAM competencies purposely to generate a quality STEM workforce, highly technological literate citizens and competent individuals to vitalize the national economy (Jho et al., 2016). STEAM education in Korea is in line with STEM education policy in other countries but with the inclusion of art as another discipline (Kang, 2019).

2.4. Neuroscience

Broadly speaking, the concept of neuroscience involves the scientific study of the human brain and the nervous system from a multidisciplinary perspective to determine how it works. Neuroscience is also often referred to as the study of the biological basis for behavior (Squire et al., 2013; Goswami, 2020). Started in the late 20th century as an emerging discipline and constantly evolving, neuroscience is now a multidisciplinary science that integrates many different fields, including psychology, biology, medicine, and many more (Goswami, 2004; Brown, 2019; Sussman, 2021). Neuroscience can be separated into five major branches (Romero, 2019; Meilleur, 2022), such as: systems, medical or clinical, cellular and molecular, cognitive, behavioral, and computational neuroscience.

Essentially, *system neuroscience* is the study of how the human nervous system and the brain relate to each other in terms of how information is encoded or decoded. These processes lead to a wide range of behaviors, including sensory perception, motor control, memory, attention, and language. This field is closely related to *medical* or *clinical neuroscience*, which besides studying the normal functioning of the human nervous system, also examines the various diseases associated with it. Some of the more common disorders include trauma, dementia, Parkinson's disease, mental illnesses, and a variety of others. Ultimately, medical neuroscience is concerned with treating and preventing these conditions.

Cellular or molecular neuroscience involves the study of the human brain's core cells and neurons. Additionally, it may include the exploration of genes, proteins, and other molecules related to the functioning of the human brain. It is based on these components that studies of brain chemistry are conducted, which are responsible for explaining the processes of perception, learning, and memory. For *cognitive and behavioral neuroscience*, this encompasses our thoughts, behaviors, emotions, and self-awareness. In general, cognitive and behavioral neuroscience focus on how the human brain affects behavior, which can range from psychology to psychiatry. Lastly, *computational neuroscience* involves the use of mathematical, physics and computer science techniques to analyze biological and clinical data on the nervous system. Typically, computational neuroscience involves the use of computers in order to simulate how the human brain functions; more specifically, how information is processed.

Educational neuroscience is an inter-disciplinary and relatively new subject often associated with the science of learning. The goal of educational neuroscience is to improve educational practice by applying findings from brain research into the classrooms. Educational Neuroscience is also referred to as 'mind, brain and education' and as 'neuroeducation.'

Educational neuroscience is helping us to shed light on subjects such as why certain types of learning are more rewarding than others; the plasticity of the brain and what happens when we learn new skills at different ages; ways of enhancing our ability to learn, and the role of digital technologies in learning, along with many others. It has potential impacts to improve educational outcomes by changing factors that influences learning, factors such as motivation, attention, ability to learn, memory, prior knowledge, stress, health and nutrition (Scando review 2022).

A report by the Royal Society in 2011 stated that while education is about enhancing learning, neuroscience is about understanding the mental processes involved in learning. This suggests that which educational practice can be transformed by science, just as medical practice was transformed by science about a century ago." –.

According to Wikipedia **"**Educational neuroscience also called Mind Brain and Education or Neuroeducation is an emerging scientific field that brings together researchers in cognitive neuroscience, developmental cognitive neuroscience, educational psychology, educational technology, education theory and other related disciplines to explore the interactions between biological processes and education. Researchers in educational neuroscience investigate the neural mechanisms of reading, numerical cognition, attention and their attendant difficulties including dyslexia, dyscalculia and ADHD as they relate to education. Educational neuroscience has received support from both cognitive neuroscientists and educators.

Research in educational neuroscience also link basic findings in cognitive neuroscience with educational technology to help in curriculum implementation for mathematics education and reading education. The aim of educational neuroscience is to generate basic and apply research that will provide a new trans-disciplinary account of learning and teaching, which is capable of informing education. A major goal of educational neuroscience is to bridge the gap between the two fields through a direct dialog between researchers and educators, avoiding the "middlemen of the brain-based learning industry."

Petitto and Dunbar (2004) argued that educational neuroscience "provides the most relevant level of analysis for resolving today's core problems in education." A survey conducted by Howard-Jones et al. (2007) found that teachers and educators were generally enthusiastic about the use of neuroscientific findings in the field of education, and that they felt these findings would be more likely to influence their teaching methodology than curriculum content. A direct link from neuroscience to education is a bridge too far, argued by some researchers (Bruer, 1997; Mason, 2009). They argued that a bridging discipline, such as cognitive psychology or educational psychology provide a better neuroscientific basis for educational practice.

However, many researchers disagreed and argued that the link between education and neuroscience has yet to realize its full potential, and whether through a third research discipline, or through the development of new neuroscience research paradigms and projects, the time is right to apply neuroscientific research findings to education in a practical and meaningful way (Goswami, 2006; Meltzoff et al., 2009).

There are many academic institutions that are beginning to establish research centers focused on educational neuroscience research around the world. One of these is the Center for Educational Neuroscience in London, United Kingdom which is an inter-institutional project between University College, London, Birkbeck and the UCL Institute of Education. The center brings together researchers with expertise in the fields of emotional, conceptual, attentional, language and mathematical development, as well as specialists in education and learning research with the aim of building a new scientific discipline, i.e., Educational Neuroscience in order to ultimately promote better learning" (Wikipedia).

In response to Bowers (2016) criticism of the practical and principled problems with how educational neuroscience may contribute to education, including lack of direct influences on teaching in the classroom. The authors of this paper concur with Gabrieli (2016) that some of his arguments are convincing especially the critique of unsubstantiated claims about the impact of educational neuroscience and the reminder that the primary outcomes of education are behavioral, such as skill in reading or mathematics. There are three major issues. Firstly, educational neuroscience is a basic science that has made unique contributions to basic education research; it is not part of applied classroom instruction. Secondly, educational neuroscience contributes to ideas about education practices that are important for helping vulnerable students. Thirdly, educational neuroscience studies using neuro-imaging have not only revealed for the first time the brain basis of neurodevelopmental differences that have profound influences on educational outcomes but have also identified individual brain differences that predict which students learn more or learn less from various curricula (Gabrieli, 2016). It is our belief that educational neuroscience can inform our understanding of learning, which in turn, choices in educational practice and the design of educational contexts, which can themselves help test and inform the theories from cognitive neuroscience and psychology. Even though educational neuroscience does not support a direct link from neural measurement to classroom practice (Howard-Jones et al., 2016).

2.4.1. Core concepts of neuroscience and educational neuroscience

A major component of neurosciences is explaining how the human brain and nervous system work. From understanding the relationship between brain and behavior to the concepts of learning and memory (Webster, 1999; Bear et al., 2015; Kandel et al., 2021). According to the Society for Neuroscience (2022), it is essential to understand how the brain works and how it is formed, and how it can help guide us through the various changes in our lives. In accordance with the Next Generation Science Standards, neuroscience core concepts (including the basic principles of neuroscience) are being integrated into the various K-12 course subjects. The eight core concepts are as follows (Society for Neuroscience, 2022): the brain is the body's most complex organ, neurons communicate using both electrical and chemical signals, genetically determined circuits are the foundation of the nervous system, life experiences change the nervous system, intelligence arises as the brain reasons, plans, and solves problems, the brain makes it possible to communicate knowledge through language, the human brain endows us with a natural curiosity to understand how the world works, and fundamental discoveries promote healthy living and treatment of disease. Using these eight core concepts throughout the K-12 curriculum will allow students to gain and learn the most important insights from decades of neuroscience research.

In higher education, the use of computer simulations (or model building) is an effective method in learning and teaching neuroscience (Rabinovich et al., 2006). Through direct engagement within the computer simulations, students are able to receive immediate feedback and reinforcement for their efforts (Av-Ron et al., 2006). Taking advantage of the core concepts, neuroscience, as previously noted, emerges as a multidisciplinary science that integrates many different fields of study that vary in depth and complexity. Therefore, in order to understand human behavior, including its complex functions like thinking and feeling, we must understand how the brain mediates these functions. Importantly, it is pertinent to note that modern neuroscience is multidisciplinary in nature, allowing it to be integrated with a variety of life science disciplines (such as genetics, molecular biology, biochemistry, biophysics and psychology), increasing our understanding of nervous system function and how neuroscience overlaps with other areas of study related to it (such as cognitive science, information science, linguistics, and experimental and clinical psychology).

As for educational neuroscience, which combines the mind, brain, and education with biology, cognitive science, development, and education (Fischer et al., 2010). Feiler and Stabio (2018) identified three emerging themes that are representative of the literature of the past three decades, namely: application of neuroscience to classroom learning, interdisciplinary collaboration, and a translator of languages (pp. 18–20). These themes clearly noted the importance of neuroscience in education (Howard-Jones et al., 2016), dispelling the myth that teachers and students are unable to integrate neuroscience into their teaching (Clement and Lovat, 2012; Bowers, 2016). Quoting the journal *Trends in Neuroscience and Education*: "*Neuroscience is to education what biology is to medicine and physics is to architecture*." In other words, this does not mean that educational psychology will be replaced by educational neuroscience. In fact, it is very important that educational neuroscience builds on the previous achievements of other disciplines and helps students develop a better understanding of how they learn.

Neuroscience can help teachers to teach in several ways, according to Barnes (2019), these include:

- Improve reading
- Deliver individualized learning for every student
- Help teachers move closer to creating learning environments, rather than simply delivering curriculum content
- Build the learning capacity of each student, so they learn more easily
- Free teachers' time to teach and add higher value learning opportunities
- Empower teachers with a new understanding about how students learn
- Help students with a range of learning difficulties

Since neuroscience offers many benefits to the learning of physics, it is our belief that by incorporating principles from neuroscience to STEM–PjBL serves as a breaking point to learn classical mechanics with the hope they can improve their beliefs about physics and learning physics STEM knowledge and skills needed in the 21st century.

3. Methodology

The quasi-experimental research design was used to collect quantitative data. This research used the two group pre-survey-post-survey of the quasi-experimental research design. The population in this study were Malaysian Form 4 students who learn physics in the secondary school and Korean second-year high school students who learn physics (Book 1). The process of extracting the samples from the population were based on the purposive sampling techniques. The Malaysian sample was selected from four intact groups at two secondary schools in Sabah, Malaysia and the Korean sample was selected from four intact groups at two high schools in Seoul, South Korea. The samples consisted of 88 Malaysian students (i.e., experimental group = 44, control group = 44) and 66 Korean students (i.e., experimental group = 33, control group = 33). The samples were considered homogenous because the participants never experienced learning physics through the integrated STEM-PjBL physics module and the chosen topics in the module were learnt for the first-time during Form 4 and second-year high school, respectively, for both samples.

3.1. Research design

This study applied a two-group pre-survey-post-survey design was employed in the quasi-experimental research design which identified as the experimental group and the control group to collect the quantitative data [55]. Both groups were given a pre-survey to measure the dependent variable by using the same instrument a week before the intervention. Then, the experimental group had received the intervention, but the control group did not receive any intervention for 8 weeks of duration. A week after the intervention, both groups were given a post-survey to measure the dependent variable again by using the same instrument. The results of pre-survey and post-survey were examined to identify the improvement of the dependent variable. The framework of the two-group pre-survey-post-survey of the quasi-experimental research design suggested by Harris et al. (2004) used as a reference for this study shown in Table 1.

TABLE 1 Two-group pre-survey-post-survey design.

Group	Implementation		
Experimental	$O1_a$	X	$O2_a$
Control	$O1_b$		$O2_b$

*$O1_a$ and $O1_b$ = Pre-Survey; X = Intervention; $O2_a$ and $O2_b$ = Post-Survey.

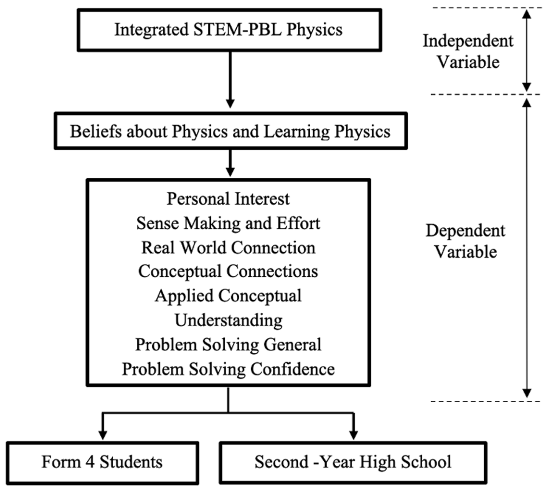

FIGURE 1
Research conceptual framework.

3.2. The integrated STEM-PjBL physics module

The Integrated STEM-PjBL Physics Module was structured and established following a thorough process by using ADDIE instructional design model. In the Integrated STEM-PjBL Physics Module, some activities may promote students' personal interest; sense-making and effort; real-world connection, conceptual connections, applied conceptual understanding, problem-solving general, problem-solving confidence, and problem-solving sophistication. These activities need students' involvement for 8 weeks, e.g., only for the experimental group. First, in groups (3–4 students), students will be given a scenario; then, they must come up with solutions to overcome the learning issue. The Integrated STEM-PjBL Physics Module consists of two chapters, i.e., the Egg Drop Project and the Spaghetti Bridge Project. Both modules will be given to the experiment groups of Form 4 students (Malaysia) and Second-year students (Korea), respectively.

The content of Integrated STEM-PjBL Physics Module was designed based on the PjBL model developed by The Buck Institute of Education (Larmer and Mergendoller, 2010). The PjBL model was used to guide the steps in implementing STEM–PjBL activities and the learning objectives were integrated into the PjBL model. Based on the PjBL model, students had to follow nine (9) steps to achieve the learning objectives for each of STEM-PjBL activity in four (4) weeks of duration. Each step had its own learning activity and students had to accomplish one step before moving to the subsequent step. After completing the first STEM-PjBL activity, students repeated the nine (9) steps of PBL model once again to implement the second STEM-PjBL activity for another four (4) weeks of intervention. The nine (9) steps in implementing STEM-PjBL activities provide guidelines for students to develop the science process. These steps and its connection with both projects, i.e., egg-drop project and spaghetti bridge is shown in Table 2.

3.3. Data collection procedures

Data was collected quantitatively using The Colorado Learning Attitude about Science Survey (CLASS). CLASS was developed based on the Maryland Physics Expectation Survey (MPEX) (Redish et al., 1998) and the Views about Science Survey (VASS) (Halloun and Hestenes, 1996). It was developed to probe students' beliefs about physics and learning physics (Adams et al., 2006). CLASS focuses on the aspects of epistemology and student thinking, making it suitable to explore students' beliefs about the nature of physics knowledge and learning. In addition, CLASS is not course-specific and ideal for students at any level of physics (Perkins et al., 2006). CLASS consists of 41 concise and clear items, and the total time required to complete the survey is 10 min or less (Adams et al., 2006; Mistades et al., 2011; Appendix A). This study was done for both countries, i.e., Malaysia and Korea, because even though both countries implemented STEM and STEAM for more than 10 years, many teachers and students are struggling with curriculum achievement and the progress is considered slow (Shahali et al., 2017; Kang, 2019).

CLASS, initially in English, was translated into both Malay and Korean through a rigorous translation process called forward translation and back translation by two language experts in each research area to maintain the originality of CLASS (Bowles and Stansfield, 2008). The quantitative data were analyzed through SPSS Version 26.0. Figure 1 shows the conceptual framework used in this research. The independent variable is the integrated STEM-PjBL Physics Module. In contrast, the dependent variables are the eight subcategories of beliefs about physics and learning physics, e.g., personal interest, sense-making and effort, real-world connection, applied conceptual understanding, problem-solving general, problem-solving confidence, and problem-solving sophistication.

4. Results and analysis – Inferential statistical analysis

A paired samples t-test was conducted to evaluate the impact of integrated STEM-PjBL physics module intervention on students' beliefs about physics and learning physics based on the students' scores in CLASS and the results of the test are shown in Table 3. In terms of Malaysian students' perspective, there was a statistically difference increase in beliefs about physics and learning physics in the experimental group from the pre-survey ($M = 3.23$, SD = 0.17) to the post-survey ($M = 4.11$, SD = 0.15), t (43) = −23.89, $p < 0.001$ (two-tailed). The mean increase was 0.88 with a 95% confidence interval ranging from −0.96 to −0.81. In addition, there was no statistically difference decrease in beliefs about physics and learning physics in the control group from the pre-survey ($M = 3.25$, SD = 0.19) to the post-survey ($M = 3.23$, SD = 0.17), t (43) = 0.31, $p = 0.760$ (two-tailed). The mean decrease was 0.02 with a 95% confidence interval ranging from −0.06 to 0.08.

In terms of Korean students' perspective, there was a statistically difference increase in beliefs about physics and learning physics in the experimental group from the pre-survey ($M = 3.05$, SD = 0.16) to the

TABLE 2 The nine steps and it's its connection with both projects, i.e., egg-drop project and spaghetti bridge.

Steps	Egg drop project activities	Spaghetti bridge activities
Step 1–build the culture.	Facilitator presents about:	Facilitator presents about:
	• STEM-PjBL as an approach to learn physics	• STEM-PjBL as an approach to learn physics
	• The procedures on how to use the STEM-PjBL physics module	• The procedures on how to use the STEM-PjBL physics module
Step 2–group setting–students developed observation skill by planning events in implementing STEM-PjBL activities chronologically after receiving details about the activities.	i. Group formation	i. Group formation
	ii. Establish group rules	ii. Establish group rules
	iii. Define roles of each member	iii. Define roles of each member
Step 3–essential question–students developed communication skill by brainstorming and communicating on draft solutions about the essential question and presented the draft solutions through sketches. Besides that, students developed classification skills by choosing the best design to be developed as a final product by considering the manipulative, responding and constant variables.	How to protect an egg from breaking when it falls from a certain height by using permissible materials; toothpicks, glues and a raw egg?	How to construct a stronger spaghetti bridge that is capable of holding more loads by using permissible materials; spaghetti sticks and glues?
	Based on the essential question, each group:	Based on the essential question, each group:
	i. Brainstorm on the draft solutions	i. Brainstorm on the draft solutions
	ii. Present the ideas through sketches	ii. Present the ideas through sketches
	iii. Choose the best design of the egg protector by comparing variables	iii. Choose the best design of the spaghetti bridge by comparing variables
	iv. Group reflection	iv. Group reflection
Step 4–sustained inquiry–students developed valuing skill by finding additional information about related physics concepts and relating the concepts into their design. The students also developed experimentation skill by constructing prototype and carried out a simple experiment to test the prototype. Students also developed interpretation skill by interpreting the results from the experiment and consequently drawing conclusions to improve the design.	Each group:	Each group:
	i. Find resources and additional information about related physics concept with the egg drop project	i. Find resources and additional information about related physics concept with the spaghetti bridge project
	ii. Construct the prototype	ii. Construct the prototype
	iii. Make improvement by experimenting	iii. Make improvement by experimenting
Step 5–decision making–students developed prediction skill by securing the ultimate design to be developed as final product after discussion was made in the group.	Each group:	Each group:
	i. Compare and reason the results after testing the prototype of the egg protector	i. Compare and reason the results after testing the prototype of the spaghetti bridge
	ii. Discuss and secure the ultimate design to be developed as the final egg protector	ii. Discuss and secure the ultimate design to be developed as the final spaghetti bridge
Step 6–Execute the Solution–students developed communication skill by constructing the final product as planned.	Each group:	Each group:
	i. Construct the final product by using provided materials:– Toothpicks, superglues or hot glue gun and a raw egg	i. Construct the final product by using provided materials:– Spaghetti sticks, superglues or hot glue gun
	ii. Communicate their progress	ii. Communicate their progress
	iii. Group reflection	iii. Group reflection

(Continued)

TABLE 2 (Continued)

Step 7–public product–students developed measuring skill by measuring physical quantities by using appropriate instruments and avoid errors when taking measurements. Besides that, students developed experimentation skill by carrying out a simple experiment to test the final product. Students also developed interpretation skill by drawing conclusions based on the results from the experiment.	Each group:	Each group:
	i. Take measurements for the mass of the egg protector, height of the egg protector before dropping and the time traveled for the egg protector before touch the floor without errors.	i. Take measurements for the mass of the spaghetti bridge
	ii. Egg drop testing and public viewing	ii. Spaghetti bridge testing and public viewing
	iii. Interpret the results after the egg drop testing	iii. Interpret the results after the spaghetti bridge testing
	iv. Group reflection	iv. Group reflection
Step 8–assess student learning–students developed forming questions and hypotheses skills by solving physics problems in the module.	Each group:	Each group:
	i. Make connections between the equations of linear motions with the egg drop testing activity to solve physics problems	i. Identify the maximum loads which the spaghetti bridge can hold before the collapse.
	ii. Interpret the motion of the egg protector in the velocity-time graph	ii. Calculate the spaghetti bridge performance
	iii. Make connections between the momentum with the egg drop project	iii. Learn from observation
	iv. Make connections between the impulsive force with the egg drop project	iv. Name the type of bridge constructed in the spaghetti bridge project
	v. Relate the impulsive force with daily life situations:–Safety features in vehicles The use of mattress in high jump	v. Make connections between the effects of a force with the spaghetti bridge project
	vi. Make connections between the kinetic energy with the egg drop project	vi. Make connections between the gravity with the spaghetti bridge project
	vii. Make connections between the gravitational energy with the egg drop project	vii. Make connections between the forces in equilibrium with the spaghetti bridge project
	viii. Make connections between the kinetic energy and the gravitational energy	viii. Relate the gravity and the forces in equilibrium with daily life situations
	ix. Communicate their progress	ix. Communicate their progress
	x. Group reflection	x. Group reflection
Step 9–Evaluate the Experience–students developed communication skill by sharing their opinions, beliefs and attitudes about the STEM-PjBL activities	i. Focus group discussion	i. Focus group discussion
	Share their opinions, beliefs and attitudes about the egg drop project with the other groups	Share their opinions, beliefs and attitudes about the spaghetti bridge project with the other groups
	ii. Group video presentation	ii. Group video presentation
	iii. Group reflection	iii. Group reflection

post-survey ($M = 3.41$, $SD = 0.17$), $t\ (32) = -15.45$, $p < 0.001$ (two-tailed). The mean increase was 0.36 with a 95% confidence interval ranging from −0.41 to −0.31. In addition, there was no statistically difference decrease in beliefs about physics and learning physics in the control group from the pre-survey ($M = 3.10$, $SD = 0.17$) to the post-survey ($M = 3.07$, $SD = 0.16$), $t\ (32) = 0.82$, $p = 0.420$ (two-tailed). The mean decrease was 0.03 with a 95% confidence interval ranging from −0.04 to 0.09.

H1: There is no significant difference in beliefs about physics and learning physics between pre-survey and post-survey for control group among Malaysian students and Korean students.

H2: There is no significant difference in beliefs about physics and learning physics between pretest and posttest for experimental group among Malaysian students and Korean students.

H1 is *accepted* - There is no significant difference in beliefs about physics and learning physics between pre-survey and post-survey for control group among Malaysian students and Korean students.

H2 is *rejected* - There is significant difference in beliefs about physics and learning physics between pre-survey and post-survey for experimental group among Malaysian students and Korean students.

An independent samples *t*-test was also conducted to compare students' beliefs about physics and learning physics between the experimental group and the control group after the intervention (post-survey) based on the students' scores in CLASS and the results of the survey are shown in Table 4. In terms of Malaysian students' perspective, there was a statistically significant difference in beliefs about physics and learning physics between the experimental group ($M = 4.11$, SD = 0.15) and the control group ($M = 3.23$, SD = 0.17) in the post-survey, $t\ (86) = 25.12$, $p < 0.001$ (two-tailed). In addition, the assumption of homogeneity of variances was tested and not violated *via* Levene's Test, $F\ (86) = 0.88$, $p = 0.351$. The magnitude of the difference in the means (mean difference = 0.88, 95% CI: 0.80 to 0.94) indicated a large effect size with Cohen's d = 5.42.

In terms of Korean students' perspective, there was a statistically significant difference in beliefs about physics and learning physics between the experimental group ($M = 3.41$, SD = 0.17) and the control group ($M = 3.07$, SD = 0.16) in the post-survey, $t\ (64) = 8.24$, $p < 0.001$ (two-tailed). In addition, the assumption of homogeneity of variances was tested and not violated *via* Levene's Test, $F\ (64) = 0.28$, $p = 0.599$. The magnitude of the difference in the means (mean difference = 0.34, 95% CI: 0.26 to 0.42) indicated a large effect size with Cohen's d = 2.06.

The results of the inferential statistical on the quantitative data showed that integrated STEM-PjBL physics module was able to give a significant improvement toward Form 4 and the second-year high school students' beliefs about physics and learning physics. Meanwhile, traditional instruction showed no influence on students' beliefs about physics and learning physics.

> *H3*: There is no significant difference in beliefs about physics and learning physics between the experimental group and the control group after the post-survey among Malaysian students and Korean students.

H3 is *rejected* - There is significant difference in beliefs about physics and learning physics between the experimental group and the control group after the posttest among Malaysian students and Korean students.

4.1. Analysis of hypothesis

It is not surprising that H3 is rejected. There are many benefits STEM-PjBL offer to students in learning (Uden and Beaumont, 2006). These include:

- STEM-PjBL embodies the principles of constructivist learning
- STEM-PjBL promotes critical thinking skills in students
- STEM-PjBL promotes team working skills
- STEM-PjBL promotes deep learning
- STEM-PjBL helps students to develop metacognitive skill
- STEM-PjBL promotes problem solving skills

From the neuroscience perspectives, the following reasons are why STEM -PjBL was considered to be a better approach for students to learn physics.

i. Collaborative Learning Reduces Stress

Emotion plays a crucial role in learning. According to Kaufer (2011), the idea that how we feel influences how we are able to learn known as the "affective filter hypothesis," stress, our emotion state influences learning, memory and decision making. In neuroscience, stress activates the amygdala, the segment of the brain connected with emotions and fear. The amygdala sends information to the hippocampus, the brain region associated with learning and memory. We learn and remember differently when the amygdala is firing. Kaufer (2011) argues that the stress response - popularly known as the "fight or flight" response — is chemically understood as the production of a variety of hormones, most significantly cortisol. When the stress is related to an emergency, cortisol is released by the adrenal gland into the brain to help us to combat or avoid the situation. But in chronic stress, the amygdala is constantly activated that has a negative effect on decision making resulting in decreased ability in learning.

In STEM-PjBL, as the students are working together and sharing knowledge, the burden of decision making is no longer falls on a single individual. It is a shared decision and thus reducing the stress that otherwise would happen.

ii. STEM-PjBL is Active Learning

Voss et al. (2011) argue that there is a difference between passive and active learning from a neurobiological perspective. They argued that volitional control is an omnipresent determinant of exploratory behaviors that occur whenever an organism is unconstrained in interactions with the environment. According to Kaufer (2011), optimized learning is produced in active learning when there is recruitment of multiple cortical areas and cross talk with the hippocampus in the brain. Kaufer (2011) furthers argues Active learning (volitional control) is advantageous for learning because distinct neural systems related to executive functions (planning or predicting, attention and object processing) are dynamically activated and communicate with the hippocampus, to enhance its performance.

iii. *STEM-PjBL Enables Students to Generate Information*

In STEM PjBL, students can generate information by linking new information to knowledge they already have because this activates our hippocampus. This happens through social information where students link their knowledge with knowledge that other students share as well as knowledge builds on knowledge known as metacognition (Voss et al., 2011).

iv. Learning in STEM PjBL is About Solving Problems

Traditional learning is where someone is told what someone else wants them to know and then the former is expected to transfer that knowledge into the workplace. Neuroscience shows that people are far more motivated to change their behavior and to adopt new ways of working when they have the insight from themselves. Creating insight requires a very different approach to delivering information. The

TABLE 3 Results of paired samples *t*-test for students' beliefs about physics and learning physics.

Group		Survey	Mean	SD	*t*	DF	*p* (2-tailed)	Mean difference
Malaysian student	CG ($N=44$)	Pre-survey	3.25	0.19	0.31	43	0.760	0.02
		Post-survey	3.23	0.17				
	EG ($N=44$)	Pre-survey	3.23	0.17	−23.89	43	<0.000*	−0.88
		Post-survey	4.11	0.15				
Korean student ($N=33$)	CG ($N=33$)	Pre-survey	3.10	0.17	0.82	32	0.420	0.03
		Post-survey	3.07	0.16				
	EG ($N=33$)	Pre-survey	3.05	0.16	−15.45	32	<0.000*	−0.36
		Post-survey	3.41	0.17				

*Shows significant difference at $p<0.001$.
EG, Experimental Group; CG, Control Group; Malaysian Student, Form Four; Korean Student, Second Year.

TABLE 4 Results of independent samples *t*-test for students' beliefs about physics and learning physics.

Group		M	SD	Levene's test	*t*-test				
				F	*p*	*t*	DF	*P* (2-tailed)	Mean difference
Malaysian student	CG ($N=44$)	3.23	0.17	0.88	0.351	25.12	86	<0.000*	0.88
	EG ($N=44$)	4.11	0.15						
Korean student	CG ($N=33$)	3.07	0.16	0.28	0.599	8.24	64	<0.000*	0.34
	EG ($N=33$)	3.41	0.17						

*Shows significant different at $p<0.001$.
EG, Experimental Group; CG, Control Group; Malaysian Student, Form Four; Korean Student, Second year.

information needs to be put in context for the learner. The learner then needs help to experience for themselves their new understanding followed by helping them to think about how they can apply their new understanding to their own role or their job.

Neuroscience indicates that a different way of designing and delivering learning is required. The emphasis now needs to be on how to get people's attention and how they can retain what they have learned. Engagement is essential to applying what has been learned. If people understand what their learning means in practical terms to their job, have clear goals about what to do with their learning and get a sense of reward for adopting new behaviors, then what they have learned is far more likely to stick.

v. Neuro-Scientific Principles Complement and Connect with Socio-Constructivist Principles of Project-Based Learning

The well-established socio-constructivist principles of PjBL are closely connected and complementary with neuro-scientific principles of teaching and learning. It postulates that student constructs knowledge based on the prior knowledge and experiences of the learners. In STEM-PjBL, Learners also exchange experiences with their peers (Savery and Duffy, 1995; Richardson, 2003).

4.2. STEM PjBL guidelines for learning from neuroscience

Principles of neuroscience can be used by teachers to help students to learn better. Firstly, understanding how the brain works helps the teacher to plan lessons and choose methods that align with neuroscience research for learning. Secondly, research from neuroscience can help teachers to understand how the behavior of students is influenced by how the brain works and environment, genetics, and perceptions. Thirdly, research from neuroscience enables us to shed light on important topics related to how the brain learns such as including neuroplasticity, memory, metacognition, mindfulness, retrieval strategies, reflection, motivation, and prior knowledge. Fourthly, neuroscience helps us to understand how students' brains are affected by factors such as emotion, exercise, sleep, motivation, and social encounters, to help us to choose the best help to give to students (Uden et al., 2022). The following principles from neuroscience can be used to help students to implement STEM-PjBL.

- Prior knowledge is important

Neuroscience studies (Bransford et al., 2000) revealed that the learning process leads to the creation of connections between several neural networks of different brain areas (Morris et al., 1988). Neurons connect each other by means of gates that are functionally modulated by neurotransmitters in the so-called synaptic junctions (Beale and Jackson, 1990). The long-lasting learning occurs when the connections between the neurons are strong and the networks are wide (Sousa, 2010; Fregni, 2019). It is important to link learning with prior knowledge.

- Use images to help students to understand abstract concepts.

The reason is that neuroscience research reveals that images such as comics help students to understand abstract concepts by making connections with real world situations (Bolton-Gary, 2012).

- Rehearsal information regularly

Because the synaptic strengthening between neurons may be weaken over time. It is important to retrieve information periodically (Karpicke et al., 2009). There must be opportunities for given to students by teachers to retrieve the concepts taught so as to allow metacognition to strengthen the connections between the neural networks. Teachers should change the type and duration of stimulus regularly

- Attention is important in learning.

According to neuroscience research, (Sousa, 2010), the teacher should change the type and the duration of the stimulus to foster learning because our brain filters out constant and repetitive information (Fregni, 2019).

- Pay attention to stress and anxiety

Research from neuroscience consider stress and anxiety are important factors that can affect learning. According to Fregni (2019), Too little and too much stress decrease learning. Moderate stress is beneficial if related to the learning context.

- The neuroscience of motivation

According to Willis (2010), intrinsic motivation is promoted by dopamine, a brain chemical that gives us a rush of satisfaction upon achieving a goal we have chosen. When dopamine levels rise, so does one's sense of satisfaction and desire to continue to sustain attention and effort. Increased dopamine can also improve other mental processes, including memory, attention, perseverance, and creative problem-solving.

Willis (2019) argues that meeting desired choices, interacting with peers, movement, etc. releases Dopamine in the brain. It is possible to help students to maintain or boost motivation by knowing what boosts students' dopamine levels. Giving choice to students can be used to increase students' level of intrinsic motivation. This helps to shift responsibility for learning to students who now own the learning. Students will learn to develop the skills of evaluating, selecting, and following through with good choices (Willis, 2019)

- *Neuroscience principles for engagement and retention* The following principles from neuroscience can be used by teachers to promote engagement and retention in students (Ovation, 2021).

i. Break content into bite-sized chunks

Chunking can be used to help students to remember. Chunking is needed because the number of information a person can hold is seven, plus or minus two. Chunking allows the brain to digest and assimilate content better by making it easier to integrate to our long-term memory.

ii. Introduce a jolt

Human attention span is only 10 to 15 min. Attention is greater when we can introduce something new or different such as visual aid or humor, thus breaking the boredom.

iii. Enhance the relevancy of learning

It is important to show the learners what is relevant and important at the first 5 min of the lesson. This is because relevance plays a crucial role in cognition. When information is perceived as relevant, cognitive efforts significantly increase, leading to much higher cognitive effects.

iv. The Spacing effect

Learning should be spaced out. Crammed, intense learning over an extended period causes the brain to take in fewer facts. Students learn better by spreading out the lesson and review over time instead of engaging in one-time, overloaded top-down sessions.

v. Create a multisensory experience Students learn best when all their senses are engaged rather than using one sense.
vi. Trigger the right emotions

Emotion affects learning. It is important to encourage learners and make sure they feel welcome and cared for. Triggering the right emotions can help attendees learn better and increase overall engagement during a session.

5. Discussion

This study demonstrates the effect of integrated STEM-PjBL physics learning to students' beliefs about physics and learning physics. Our Findings show that integrated STEM-PjBL physics learning intervention resulted in a positive shift in students' beliefs about physics and learning physics, but the traditional instruction shows no influence on students' beliefs about physics and learning physics for both Malaysian and Korean perspectives. Physics instruction is the significant factor that affects the shift in students' beliefs about physics and learning physics (Hammer, 1994; Wieman and Perkins, 2005; Madsen et al., 2015).

There has been much research carried out on STEM-PjBL that show positively shifted student beliefs in various ways, For example, Han's (2017) study showed that students who were positive toward PjBL components (i.e., technology-based learning, self-regulated learning, and hands-on activities) were more likely to have the intent to pursue a STEM-PjBL. STEM-project-based learning increases effectiveness, creates meaningful learning and influences student attitudes in future career pursuit; (Samsudin et al., 2017). Diana et al. (2021) findings show the effectiveness of the application of PjBL in STEM learning that improve students' cognitive, affective, and psychomotor abilities; whereas in Bhakti et al. (2020) study, they found that STEM-PjBL, improved student science process skills in all indicators of the science process skills, where students also give a positive response to learning, because they feel they have more understanding, improved motivation and learning interests.

Our study is unique in that we want to investigate if there was any shift between traditional teaching and the use of STEM-PjBL by students in their belief in physics and learning physics. Our result clearly reveals that our STEM-PjBL shows a significant positive shift in students' belief in physics and learning physics after being exposed to the STEM-PjBL approach. Another important difference between our study and others is that we have incorporated neuroscience research in our implementation of STEM-PjBL. Educational neuroscience, the study of the brain's development, structure, and function, is a powerful discipline that can be very helpful to teachers to help students to learn better.

The positive shift of students; belief in physics and learning physics can be explained by the principles of educational neuroscience. Students at the STEM-PjBL class learned well because the learning was active. According to neuroscience active learning experiences promote changes in neural connections that are fundamental for learning in the brain. Simply listening to a lecture will not lead to learning. Neuroscience research shows us that active engagement such as facilitation in PjBL is a powerful way to learning.

In STEM-PjBL, the recall of prior knowledge is important, students were constantly challenged about what they knew. Students should be stimulated to connect the new concepts with the concepts they already knew (Sousa, 2010). By doing it, the students create new neural network paths and create a more distributed network that facilitates long lasting learning (Draganski et al., 2004). The synaptic strength in our brain may be weaken over time. To overcome this, it is necessary to retrieve the information periodically. It is important that we provide opportunities for retrieving the concepts learned to allow metacognition to strengthen the connections between the neural networks. In STEM-PjBL, this was happening all the time when students challenged each other to solve the problem as well as with the teacher.

Additionally, In STEM-PjBL students took control of their own learning, and they were able to make choices to engage in learning and received immediate feedback on their progress toward their chosen goals. This motivated them. When students interacted with their peers, working on challenging problems, their dopamine levels increased, and this help them to maintain their motivation. The brain is the core of human thought, consciousness, emotion, and memory. It is only reasonable that we apply the principles of neurosciences to help our students to learn better. Our research has found that by incorporating principles of neuroscience have impacted student shift in physics and learning physics.

6. Conclusion

Our study shows that integrated STEM-PjBL physics learning has significantly improved Form 4 and second-year high school students' beliefs about physics and learning physics after the intervention. Students bring their existing beliefs about physics and learning to the classroom in which these beliefs may affect learning and how they interpret what they have learned in a physics class. This study applied integrated STEM education based on the principles of neuroscience in the form of interdisciplinary approach through PjBL to learn classical mechanics in secondary education in Malaysia and Korea. We did this this because integrated STEM education at the secondary education level is not well established in Malaysia although the Ministry of Education Malaysia has introduced the Malaysia Education Blueprint (2013–2025) to promote STEM education among secondary school students since 2013. At the same time, the Ministry of Education Korea has also issued a nationwide policy since 2011 to promote integrated STEAM education in secondary education that focuses on multidisciplinary approach. Despite the increase in STEAM education efforts, numerous studies have reported Korean teachers' difficulties with integrated STEAM education especially in implementing a multidisciplinary approach. In recent years, the interdisciplinary approach is getting more attention in Korea, but limited research on the effect of the interdisciplinary nature of STEAM. It is important to investigate if integrated STEM-PjBL physics learning by students in both Malaysia and Korea would improve their belief about physics and physics learning based on the principles from neuroscience. Our study gives us positive outcome in both countries. Moreover, in our study we have identified principles from neuroscience that have important implications to help teachers to implement STEM-PjBL in physics learning.

Although the sample is small, we believe that our approach can be used by teachers who want to teach physics to students. This approach will help students to improve their belief about physics and learning physics. More empirical studies are needed to validate the approach. We are currently expanding the framework to the teaching of other subjects such as Chemistry and Mathematics. Further studies will be to incorporate Technology Pedagogy Content Knowledge (TPACK) to our framework for on demand online learning to meet the current trends of online learning due to the pandemic.

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.

Ethics statement

The studies involving human participants were reviewed and approved by Educational Planning and Research Division, Ministry of Education (MoE), Malaysia. Written informed consent to participate in this study was provided by the participants' legal guardian/next of kin.

Author contributions

LU and FS: conceptualization. FS and JR: methodology, validation, formal analysis, investigation, resources, and data curation. JR: software and visualization. LU, FS, and GC: writing, supervision, and writing–editing. LU and GC: literature review. FS: project administration and funding acquisition. All authors contributed to the article and approved the submitted version.

Funding

This work was supported by the Research Management Center Universiti Malaysia Sabah, Grant Number: UMSGreat0210-1/2018.

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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frontiers | Frontiers in Psychology

TYPE Hypothesis and Theory
PUBLISHED 20 July 2023
DOI 10.3389/fpsyg.2023.1220664

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OPEN ACCESS

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University Malaysia Sabah, Malaysia

*CORRESPONDENCE
Tracey Tokuhama-Espinosa
traceytokuhamaespinosa@fas.harvard.edu

†These authors have contributed equally to this work and share first authorship

RECEIVED 11 May 2023
ACCEPTED 21 June 2023
PUBLISHED 20 July 2023

CITATION
Tokuhama-Espinosa T, Simmers K, Batchelor D, Nelson AD and Borja C (2023) A Theory of Mental Frameworks.
Front. Psychol. 14:1220664.
doi: 10.3389/fpsyg.2023.1220664

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A Theory of Mental Frameworks

Tracey Tokuhama-Espinosa[1,2*†], Kristin Simmers[3†], Danielle Batchelor[1†], Allen Drew Nelson[1†] and Cynthia Borja[2,4†]

[1]Harvard University Extension School, Faculty of Arts and Sciences, Cambridge, MA, United States, [2]Connections: The Learning Sciences Platform, Quito, Ecuador, [3]Neag School of Education, CT Institute for Brain and Cognitive Science University of Connecticut, Storrs, CT, United States, [4]The Decision Lab, Independent Behavioral Science Research, Montreal, QC, Canada

Problem-solving skills are highly valued in modern society and are often touted as core elements of school mission statements, desirable traits for job applicants, and as some of the most complex thinking that the brain is capable of executing. While learning to problem-solve is a goal of education, and many strategies, methodologies, and activities exist to help teachers guide the development of these skills, there are few formal curriculum structures or broader frameworks that guide teachers toward the achievement of this educational objective. Problem-solving skills have been called “higher order cognitive functions” in cognitive neuroscience as they involve multiple complex networks in the brain, rely on constant rehearsal, and often take years to form. Children of all ages employ problem solving, from a newborn seeking out food to children learning in school settings, or adults tackling real-world conflicts. These skills are usually considered the end product of a good education when in fact, in order to be developed they comprise an ongoing process of learning. “Ways of thinking” have been studied by philosophers and neuroscientists alike, to pinpoint cognitive preferences for problem solving approaches that develop from exposure to distinct models, derived from and resulting in certain heuristics used by learners. This new theory paper suggests a novel understanding of the brain’s approach to problem solving that structures existing problem-solving frameworks into an organized design. The authors surveyed problem-solving frameworks from business administration, design, engineering, philosophy, psychology, education, neuroscience and other learning sciences to assess their differences and similarities. This review lead to an appreciation that different problem-solving frameworks from different fields respond more or less accurately and efficiently depending on the kinds of problems being tackled, leading to our conclusion that a wider range of frameworks may help individuals approach more varied problems across fields, and that such frameworks can be organized in school curriculum. This paper proposes that explicit instruction of “mental frameworks” may help organize and formalize the instruction of thinking skills that underpin problem-solving–and by extension–that the more such models a person learns, the more tools they will have for future complex problem-solving. To begin, this paper explains the theoretical underpinnings of the mental frameworks concept, then explores some existing mental frameworks which are applicable to all age groups and subject areas. The paper concludes with a list of five limitations to this proposal and pairs them with counter-balancing benefits.

KEYWORDS

mental frameworks, problem-solving, critical thinking, learning how to learn, mind-brain-education, higher order cognitive functions, mental schemata

1. Introduction

Education has long been seen as a social equalizer in society (Bernardi and Ballarino, 2016), and educational goals regularly adapt to modern times (e.g., Bird and Bhardwaj, 2022) in terms of *what*, *how*, and even *why* things are taught (Darling-Hammond et al., 2020). While the specific content of the educational experience is regularly debated, a constant over the past few decades has been to emphasize *how* to think, not *what* to think, in order to encourage life-long learning (Velez and Power, 2020). Indeed, the formation of "deep thinkers" (Helm, 2015) and "deep learners" (Fullan et al., 2018) is perceived as a way of time-proofing educational content by learning a *process* to approach problems (Gunawardena and Wilson, 2021). Some argue that by helping students to learn to think for themselves, society is also helping its members develop literacies which may help protect one's values, by shielding against invasions from undue influences on social media and so called "fake news" (Paul and Elder, 2019). Thinking skills are needed to resolve both simple and complex problems, as explicitly learning critical thinking skills improve problem-solving, just as rehearsal of problem-solving enhances overall thinking (Belecina and Ocampo, 2018). This "chicken and egg" relationship of thinking to problem solve (or problem-solving to think) has often led to these concepts being used interchangeably in the literature (e.g., Shanta and Wells, 2022). Problem-solving emerged as a desirable skillset in modern education about a 100 years ago when educators suggested that the ability to resolve problems outside of school subject areas displayed transfer and higher order thinking, which was also the responsibility of education (e.g., Dewey, 1930; Burton, 1929). Burton went so far as to call problem-solving one of five forms of learning, and Dewey noted that, "Education is not preparation for life; education is life itself" (Dewey, 1930, p. 267).

Current school trends designed to respond to the call for problem-solvers has led to the successful application of pedagogical approaches, such as problem-based learning (e.g., Uluçınar, 2023), inquiry-based practice (e.g., Öztürk et al., 2022), and personalized learning through technology (e.g., Wang et al., 2022). While such interventions tend to have a positive result on problem-solving skills, they are not organized, structured, nor presented as a single curriculum.

1.1. Problem statement

There are differing opinions about the best way to teach problem-solving skills in schools. Most of the literature offering evidence-based interventions surround techniques (e.g., Proctor, 2020), strategies (e.g., Zhao et al., 2019), methodologies (e.g., Casiraghi and Aragão, 2019), and activities for critical and creative thinking (e.g., Akgun and Sharma, 2023), showing a range of excellent approaches and spanning all age groups. However, there is less literature on how all these become habituated as thinking *processes* in the brain, which over time (starting in early childhood and consolidating in adulthood), become heuristic approaches to problem solving. We propose that the habituated heuristics of thinking explain the speed and agility of problem solving. Furthermore, we suggest that a person with many different possible mental frameworks to choose from in the problem-solving process is like the mechanic with an extensive tool box, or the painter with a broader pallet of colors, whereby more options enhance the likelihood of a good outcome. This exposure to different problem-solving approaches also explains why certain complex or dynamic problems may be particularly challenging for people possessing a limited number of frameworks.

Wicked problems, which Rittel and Webber (1973) identified as problems whose solutions change depending on how they are approached and by whom, are never fully resolved and do not involve binary answers. We suggest that *all* problems are wicked problems for the novice learner. Because the learner is not well-versed or rehearsed in the ways problems are identified and resolved, they may not know where to begin, or have the self-efficacy to start experimenting in an effort to refine their approach. Thus, we further propose that explicit teaching of and implicit exposure to different mental frameworks will equip learners with more, and eventually better, choices for problem resolution over time. Exposure to a greater variety of mental frameworks for problem solving also has the potential of increasing one's confidence to begin problem solving tasks in the first place. The more rehearsal one has with frameworks, the more automated and rapid the ability to respond heuristically. We propose that the quantity of exposure should be matched by the quality and variety of approaches. We believe that the *Theory of Mental Frameworks* is unique in approaching problem-solving at all age levels and within all subject areas as a life-long learning process achieved through rehearsal and resulting in heuristics. The ability to effectively employ varying frameworks then, matters more than the specific subject matter or environment in which the problem may be tackled.

1.1.1. The problems of problem-solving: tool access and use

To effectively solve any problem, whether simple or complex, it is essential to have the right tools, processes, and strategies in place. Although it is possible to solve problems without the proper tools, the process will likely be more challenging, less efficient, and the range of solutions more limited (Lowes, 2020). This paper identifies some of the mental frameworks that may be used to solve complex problems in particular. "Complex problem-solving is a collection of self-regulated psychological processes and activities necessary in dynamic environments to achieve ill-defined goals that cannot be reached by routine actions," according to Dörner and Funke (2017, p. 6), which we label *mental frameworks*. Mental frameworks are processes that may be learned and accessed both implicitly (unconsciously) and explicitly (consciously), and which may be recalled automatically with practice. The researchers elaborate further on the broader problem-solving process, which, "combines cognitive, emotional, and motivational aspects, particularly in high-stakes situations" (p. 1,153). These emotional and motivational aspects require their own set of learned strategies, known as *coping* in more high-stakes situations, to support the explicit cognitive strategies involved. They are also supported through the cultivation of social emotional learning (SEL) skills that serve as "emotional rudders," helping to guide problem-solvers through relational dynamics that accompany these processes, both in and out of school settings (Immordino-Yang and Damasio, 2007, p. 3). Importantly, complex problem-solving tends to involve some degree of collaboration or interaction and is not typically processed by the thinker in an entirely independent manner.

Everything learned can be defined as knowledge, skills and/or attitudes (Wiggins and McTighe, 2005) which De Houwer and colleagues explained are gained through experience and "ontogenic adaptation" due to "changes in behavior" based on "regularities in the environment" (De Houwer et al., 2013, p. 631). This means people's belief systems about their world are modified by different kinds of experiences. By extension, problem-solving requires learning about, and then using, different mental frameworks that pull from those knowledge, skills, and attitudes learned. We propose that (a) for many learners much of this happens without awareness, and (b) one can become an expert problem solver with the intentional accumulation of frameworks gained through experience over time.

1.1.2. The potentials of problem-solving: adaptive expertise

Effective problem-solving depends on the mental tools available, and the more tools that are utilized efficiently, the better the problem solving will be. While basic domain knowledge may be sufficient for simple or familiar problems, novel or complex problems require cognitive flexibility to consider relevant prior knowledge, cross silos of field understanding, and to generate new potential solutions (Miyake et al., 2000). Cognitive flexibility refers to the ability to mentally switch between different concepts in response to a specific situation or novel context (Scott, 1962) and relates to adaptive expertise (Carbonell et al., 2014).

The concept of "adaptive expertise" was first introduced by Hatano and Inagaki (1986) as a contrast to routine expertise. In this conceptualization, both adaptive and routine experts are successful in familiar situations, but when faced with novel situations, routine experts struggle, while adaptive experts demonstrate flexibility in thinking (Schwartz et al., 2005) and are able to apply their knowledge of what approaches to use, and when and how (Carbonell et al., 2014) to find an effective solution. Adaptive experts not only apply previously acquired knowledge and skills to new and unfamiliar situations, but they also modify or restructure that knowledge as needed to solve problems in new contexts (Hatano and Oura, 2003). This requires a deep understanding of a particular domain as well as the ability to transfer knowledge to new and diverse situations (Rittle-Johnson and Star, 2007).

Furthermore, effective employment of an appropriate adaptive strategy based on the specific problem at hand, requires an assessment of both cognitive and emotional conditions. "Indeed, emotion without cognition is blind and… cognition without emotion is vacuous" (Scheffler, 1977, p. 171). This suggests there is always an emotional element to any problem, and that our responses to them inherently involve emotional processing as well. This explains why some younger children have trouble with problem-solving skills as they may not have refined emotional intelligence or social regulation skills, which are highly related. Some mental frameworks are affectively oriented while others are cognitively oriented.

Research demonstrates that mental frameworks that employ the ability to pivot emotionally or involve attitudinal shifts, such as Dweck's Theories of Intelligence (better known as Growth and fixed Mindset Theory; Dweck, 1999), Brackett's RULER approach (Brackett, 2019; Brackett and Cipriano, 2020), or Costa and Kallick's *Habits of Mind* Costa and Kallick (2000), compliment mental frameworks that focus primarily on cognitive elements, such as planning, assessing, or designing. Each contributes to the formation of a more robust toolbox, which enhances cognitive flexibility in problem-solving. Consequently, those with greater cognitive flexibility can become "adaptive experts" with the tools they possess as they respond to novel and complex situations, utilizing an effective balance of prior knowledge and generating new knowledge (Carbonell et al., 2014), which can become habituated over time. This ability to adapt and apply increasingly numerous and complex mental frameworks is growing in importance for both students and professionals as the need for critical and creative problem solving expands in the classroom and beyond (Carbonell et al., 2014).

By extension, the experience-expectant aspects of cultivating an "adaptive toolbox" for problem-solving focuses on actively developing additional thinking strategies and tools to aid in the process, according to Gigerenzer and Todd (1999). Furthermore, the researchers revealed that a key aspect when using an adaptive toolbox is the ability to recognize when a particular strategy is not working and switch to a different one, thereby using "fast and frugal" heuristics (Gigerenzer and Todd, 1999). Fast and frugal heuristics, therefore, enable individuals to make optimal decisions within the limitations of available time and knowledge. Accordingly, in order to effectively use an adaptive toolbox for problem solving, one needs to have sufficient familiarity with the tools and mental frameworks therein.

The strength of adaptive expertise, or adeptness of one's adaptive toolbox, relies on both the quality and quantity of one's exposure to a range of problem-solving frameworks. This includes both the conscious and unconscious use of tools, something which can be enhanced with intentional effort and conscientious instruction (Bayounes and Saâdi, 2022).

2. Theoretical framework

Piaget (1923) published, *The Language and Thought of the Child* in which he introduced the concept of mental schema. Mental schemata are mental structures upon which people build their knowledge of the world. Since its introduction, studies in fields as broad as philosophy (e.g., Nevid, 2007) and neuroscience (e.g., Ohki et al., 2023) have confirmed the existence of such thought organizing mechanisms in the brain (Ohki and Takei, 2018). This paper proposes to build off of Piaget's ideas of mental schema, which are conceptual understandings, and will pull from available models of mental processing to consider a *Theory of Mental Frameworks*, a collective *grouping of schemata*. While schema generally surround semantic knowledge, such as the meaning of words, we use the term *mental frameworks* to imply an understanding of the ways people habituate thinking *processes*. Earlier work on problem-solving has made the distinction of problem-solving as a product versus a *process,* including Gross and McDonald's work which stated that, "forward-looking science educators have decried the mistaken notion held by so many teachers in all curricular fields that problem-solving abilities are merely by-products of the memorization of the lesson or result almost automatically from learning a set of facts," Gross and McDonald (1958, p. 259). Just as people use the heuristics of schematic knowledge to forge implicit shortcuts in thinking and decision making (Vazsonyi, 1990), we propose they also use mental frameworks when they approach problem-solving through explicit processes.

Jean Piaget's theory of mental schema suggests that people can "expand" their mental schema by layering multiple levels of understanding to different concepts. If a person had only known one kind of "dog" in their life, the mental schema of a dog was limited. Others who had known many kinds of dogs had many ways of understanding dogs, displaying a broader mental schema, including other breeds, stuffed animals, cartoons, and other renderings. Mental schema moved beyond being a psychological theory of learning to a neurophysiologically demonstrable construct, established firmly in the literature. Relatedly, one of the most vibrant areas of neuroscientific research for the past two decades relates to the study of the neural correlates of consciousness (Chalmers, 2000). People now take mental schema for granted and it is perfectly normal to presume that others have different relationships with concepts (schema) based on their prior knowledge of the world.

Research on Theory of Mind, or the way people read each other's minds based on perspective-taking and prior knowledge, furthered the belief that mental schema could vary between individuals (Baron-Cohen et al., 1985; Baron-Cohen, 1991). The understanding that mental schema are not always shared was supported by work in psychology in the 1980s and 1990s, using false-belief task experiments (e.g., Wimmer and Perner, 1983). An understanding of Theory of Mind revealed that different people's life experiences change the knowledge base they have for meeting challenges in the world. These differences are based on unique experiences and habituated responses developed over time, namely heuristics and biases (conscious and unconscious), and behaviors. If we accept that people's mental schema are different, then it is likely their mental *frameworks* for problem solving may also differ (Chen, 1999).

Models of thinking exist across all academic fields and are used to identify the ways people contemplate, negotiate, and manage their worlds (see *Mental Models: Learn How to Think Better and Gain a Mental Edge* by James Clear, 2023 as an example). Mental frameworks to approach problem solving in education have existed for decades and are most recognizable as "problem-based learning" strategies [see Cindy Hmelo-Silver's many publications as examples, (Hmelo and Cote, 1996; Hmelo-Silver, 2004; Hmelo-Silver and Barrows, 2006)]. While we agree that "all models are wrong, but some are useful," according to Box's (1979) famous aphorism, we think that the transdisciplinary selection of mental frameworks from mind (psychology), brain (neuroscience), and education (pedagogy), often referred to as MBE, can lead to a powerful toolbox of options for all problem-solvers, be they teachers or learners.

To explore this further, we rely on the premise that how and to what extent models and frameworks are easy to employ, often determines their utility. We offer that frameworks which are easily accessible, highly transferable, and generalizable, represent good models that will be used often. The following three sections of the paper explain the nature of problem identification and solution seeking to gain an appreciation of the multi-faceted ways problem-solving can be taught in schools. This is followed by examples of mental frameworks from MBE, and a discussion of the possible utility of this Theory in educational practice.

3. Problem-solving and the brain

Learning to think in order to resolve problems involves multiple cognitive processes and uses a complex combination of neural networks in the brain, which vary depending on the task at hand (Alchihabi et al., 2021). For example, while the recollection of the meaning of a word is a relatively simple cognitive process on the surface, it is actually highly complex (Dreyer and Pulvermüller, 2018). Recalling the word meaning is one thing, however actually using it will also depend on an understanding of the contexts in which it may be employed (Ferreira et al., 2015), how it combines with other words (Grisoni et al., 2017), and who is present in the use-context (Renoult et al., 2019), among numerous other dynamic factors. Calling upon mental frameworks follows a similar process but is far more complex than recalling words. This invites exploration into how unconscious heuristics may be altered by a learner's conscious decision to learn about different mental frameworks.

Benson (2016) suggested that most cognition, including problem-solving, is framed by bias, which in turn is driven by unconscious heuristics. This type of thinking involves dozens of neural correlates and thousands of synaptic processes spread out over different cortical areas (Gnedykh et al., 2022). To find the meaning of a word in semantic memory conjures dozens of simultaneous autobiographical memories about its existence in one's life (Teghil et al., 2022; Mace and Kruchten, 2023), networks to articulate this to another person using words (Wank et al., 2020), and possibly even more, if written (James et al., 2015). Semantic memory is only one of dozens of complex processes involved in the brain's understanding and resolution of problems.

Problem-solving in the brain involves general cognition (memory, attention, executive functions; Miguel et al., 2023) as well as domain specific knowledge, such as recall of mathematical formulas, art genres, or periods of history. Sub-areas of memory include working memory (Emch et al., 2019); both procedural (van den Berg et al., 2023) and declarative (Sarathy, 2018), long-term memory, and sub-systems other than autobiographical and episodic memories, such as emotional memory tracts (Engen and Anderson, 2018). Processes related to attention include alerting attention systems (Zabelina et al., 2019), orienting attention systems (Spadone et al., 2021), and sustained attention (Fisher, 2019). Executive functions measure a range of abilities (Burgoyne and Engle, 2020); inhibitory control (Bajo et al., 2021); and cognitive flexibility (Balázs, 2019). Domain specific processes are also needed, which has to do with specialized field knowledge (e.g., Neubert et al., 2017).

As there is no cognition without emotion, there is also an abundance of literature which considers the role of affect on problem-solving. Pekrun and Loderer have led work on emotions and learning in academic settings for decades Pekrun and Loderer (2020), and their most recent review of the emotions that are influential in learning show important links between "multiple representations and perspectives" (p. 373). Furthermore, a large amount of literature explains how stress influences learning in negative as well as positive ways, related to both individual and group learning (e.g., Avry et al., 2020).

People approach problems in a number of ways, including through the use of analogical thinking to understand a current situation (Parsons and Davies, 2022), and procedural strategies to resolve problems (Sokolowski et al., 2023). Other research looks at how a person makes inferences while speaking (Jara-Ettinger and Rubio-Fernandez, 2021) to fill in gaps in knowledge, or uses social cues to learn the intentions of another (Henry et al., 2021). Some research studies the brain as it experiences "insight" versus ordinary problem solving, by gauging whether people approach problems using simple visual networks compared with higher order thinking networks (Lin et al., 2021). Yet others like Shpurov et al. (2020) and Prince and Brown (2022), seek to understand what changes in the brain when an individual approaches a problem on their own versus within a group setting. Hong and Page found that collaborative work among people who approached problems differently was actually superior to that of individual expert problem solvers Hong and Page (2004). These many different sub-elements in the neural correlates of problem-solving suggest that different combinations of thinking tasks are used during different approaches to problems.

3.1. Prioritizing problem-solving *processes* over *products*

If the collective goal of schooling is to prepare students for the future by encouraging them to think for themselves, master skills and knowledge, and innovate, as governments and organizations ranging from the U.S. Department of Education to the Organization for Economic Co-operation and Development (OECD, 2019) suggest, then learning to resolve problems using critical and creative thinking is to be expected as a regular part of teaching. Evidence shows that when the goal of problem-solving achieved through critical thinking is met, student outcomes are better, the transition to adulthood happens more seamlessly, and success in its various forms unfolds for more types of students and in more contexts (e.g., Frey et al., 2005; Linares et al., 2005; National Commission on Social, Emotional, and Academic Development, 2019; OECD, 2019). However, these goals and their associated positive outcomes tend to be at odds with many existing educational practices and systems, and may be harder to implement (Ahmadi et al., 2019). Decades of curricular focus on critical thinking and problem-solving have revealed challenges that span developmental ages and stages and various types of educational approaches (e.g., Ahmadi et al., 2019), which often do not explicitly teach mental frameworks for problem solving, but rather implicitly attempt to embed them in classroom activities.

Thinking "outside-of-the-box" which is associated with critical thinking and problem-solving, is often non-linear, as seen in most of the mental frameworks shared in this paper, such as Design Thinking, which has a more circular and iterative process (Serrat, 2017), or holonic thinking which requires constant changes in perspective taking (Tokuhama-Espinosa, in review) that underpins cognitive flexibility. This is in contrast to the single correct answer possibilities expected on a typical standardized test (Au, 2011). Divergent and creative thinking takes time and patience to generate, and depending on the subject matter, it does not always yield a singular answer or solution. Thinking outside the box centers the learning on the learner, and heavily depends on things like context (e.g., Amabile, 2018), past experiences (Acar et al., 2019), the relationship between student and teacher (Hattie, 2012; Martinez et al., 2016; Wentzel, 2016), one's social and emotional skills (Immordino-Yang and Damasio, 2007; Jones and Bouffard, 2012), and the specific risk and protective factors of a given student (e.g., Ellis et al., 2017).

These studies suggest that problem-solving cannot be nurtured in a one-size-fits-all process (e.g., Davis and Autin, 2020), but rather varies by individual and context. As a result, while schools do teach problem-solving, the realities of doing so for different types of learners across subjects, in age-appropriate ways, against the backdrop of state and national accountability measures, and within the constraints imposed by the design of a typical school day (e.g., class length, variability in student/teacher ratios) means that problem solving in schools is often reduced to single solution activities (Au, 2011) and/or infrequent activities that are not presented with enough regularity to induce the "fast and frugal" heuristics mentioned earlier. Despite a growing awareness of the importance in learning of mental processes and individual contextual factors of each student, current problem-solving in schools is still largely focused on getting to a specific, single final product (e.g., correct answers on a multiple-choice test). This problem offers an opportunity to model what society collectively hopes to teach—problem-solving—in service to the wellbeing of children and with the ultimate goal of improving teaching and learning.

3.2. Identifying and resolving problems

Many readers are familiar with the questioning stage of young children, which can start as early as two or three-years of age, in which children respond to every answer by asking "Why?" All children around the world go through this stage (Mackey, 2023) suggesting that questioning is an innate quality shared by people of all ages (Seyferth et al., 2022). Research suggests it is much harder to come up with a question than to answer one (Marzano et al., 2001), and many teachers intuit that there is a higher level of thinking involved in question formation than in question answering. The more complex nature of problem identification is also born out in neuroscientific studies. Just as multiple-choice questions are easier to answer than open-ended questions, involving fewer complex networks in the brain (Zhang et al., 2021), the retrieval of information to answer a question is less neurologically complex than formulating one (Stoewer et al., 2022). As a teaching strategy, Rothstein and Santana encourage us to *Make Just One Change: Teach Students to Ask Their Own Questions* Rothstein and Santana (2011). This is similar to real world problem-solving in which awareness of one's condition is the first step toward bettering that condition (Asy'ari and Ikhsan, 2019). Prior to resolving a problem, one must know the problem exists in the first place. Melles et al. (2015) call this "problem identification" and consider it the first step in design thinking which moves toward authentic solutions to real world problems.

Some people can tackle problems easily, even with little or no prerequisite knowledge (Salmon-Mordekovich and Leikin, 2022). That is, faced with any problem, they know steps to begin the resolution of the problem or to find creative responses. Others struggle to approach problem-solving, even within their field of expertise. They may have a hard time because they do not see the problem to be solved (Dandan et al., 2022). This suggests that identifying what constitutes a problem and knowing where to begin are difficult, often complex, and involve higher order thinking.

Both finding and resolving problems are teachable skills, and for decades teachers have been tasked with the responsibility for developing problem-solving skills (Weir, 1974; Dilekli and Tezci, 2022). Many excellent teachers manage to introduce one or more mental frameworks to facilitate problem identification and resolution in class activities, and methods such as inquiry-based learning for problem solving have shown superior learning outcomes (Hala and Xhomara, 2022). As different types of problems require different approaches, we suggest that the introduction of multiple mental frameworks in each class situation would benefit long term thinking skills in students.

Several of the mental frameworks ripe for inclusion in this review come from the learning science fields of mind (psychology), body and brain (genes and neuroscience), health (mental and physical wellbeing), and education. To illustrate the ways different mental frameworks from distinct fields may contribute to a student's toolbox of mental framework options, we will first discuss four popular frameworks for problem-solving found in education, then describe three models from psychology, followed by four frameworks from neuroscience.

4. Existing mental frameworks from education

Mental frameworks in education span a broad range of contexts. Some important models not discussed in this paper in detail, but worthy of consideration, include the sophisticated classification structures related to mental frameworks for thinking, such as Project Zero's visible thinking routine toolbox (Ritchhart et al., 2011), and for social–emotional learning, such as the Collaborative for Academic, Social, and Emotional Learning (CASEL, 2020) "wheel" framework. Other important mental frameworks often used by teachers include the Theory of Multiple Intelligences (Gardner, 1983) and the Quadruple Helix model to motivate global citizenship (Socher et al., 2021).

Educators have looked to other spaces such as the worlds of business and design in an attempt to solve the problem of how to teach problem-solving in schools (e.g., Noweski et al., 2012). Various models have been adopted and applied (e.g., Davis and Autin, 2020; Foster, 2021; Kijima et al., 2021) to include *Design Thinking* and *Understanding By Design*. Like other problem-solving models, however, these frameworks rely on important professional development and educator acceptance (Schell, 2014). Mental frameworks borrowed from business require contextual adaptation in order to be generative in school contexts.

Four mental frameworks from education that are supported by dozens, if not hundreds of studies, include those that seek **shifts in attitude** to improve the likelihood of learning, both in formal and informal contexts (e.g., ***Habits of Mind***); leverage good **planning** to resolve problems (e.g., ***Understanding by Design***); employ empathy and cognition through **design thinking**; and take stock of problem elements through **assessment** (***Compass*** and **SWOT** activities). All may be applied starting in early childhood and can be developed over the lifespan.

4.1. Shifts in attitude for problem-solving: *habits of mind*

Developed by Costa and Kallick over the past 40 years, *Habits of Mind* Costa and Kallick (2009) is a list of 16 ways to improve the likelihood of life and school success, and has been used by U.S. school districts since 1998. According to the authors, "a 'habit of mind' means having a disposition toward behaving intelligently when confronted with problems," (Costa, 2010, p. 1). This design pre-dates many of today's accepted ideas about motivation, learning, and problem-solving, which are all part of the habits.

Art Costa's work on intelligent behaviors Costa (1981) lead to a 1991 publication bringing together researchers, philosophers, and cognitive psychologists to find consensus on how to develop thinking (Costa, 1991). The Habits of Mind were formed in collaboration with Bea Kallick's contributions, which showed that each of the 16 habits could be designed and assessed as learning experiences (Costa and Kallick, 1995).

Habits of mind:

- Persisting (not giving up in the face of difficulty)
- Managing impulsivity (self-regulation)
- Listening with understanding and empathy (the ability to take others' perspectives)
- Thinking flexibly (not having a fixed mindset)
- Thinking about your thinking (metacognition)
- Striving for accuracy and precision (not settling for "good enough" but rather striving for the best)
- Questioning and problem posing (identifying areas in need of improved or better information)
- Applying past knowledge to new situations (learning from the past)
- Thinking and communicating with clarity and precision (generating and sharing ideas with accuracy)
- Gathering data through all senses (using sight, smell, taste, touch, and hearing to learn about the surroundings)
- Creating, imagining and innovating (always seeking ways to make things better)
- Responding with wonderment and awe (finding joy in everything)
- Taking responsible risks (not being compliant)
- Finding humor (not taking oneself or the world too seriously)
- Thinking interdependently (1 + 1 = 3; using the wisdom of the group; know yourself by knowing the other)
- Remaining open to continuous learning (openness)

There is evidence that people who adopt the 16 habits are better at approaching problems because they are open, do not give up, seek alternative pathways to answer questions, and use all tools available (Alhamlan et al., 2018). Research reveals benefits when the habits are adopted collectively as well as when they are used individually (Costa and Kallick, 2009). Additionally, upon review we found they overlap with elements of other focuses of learning, including executive functions (Saleh Al Rasheed and Hanafy, 2023), social–emotional learning (Alexander and Vermette, 2019), the Big Five Personality trait of openness (Abdellatif and Zaki, 2021), and the Mind, Brain, and Education Principles and Tenets (Tokuhama-Espinosa, 2014). The 16 habits of mind are useful in addressing problems that require a shift toward positive thinking (Anderson, 2021), and for problems in which the learner likely knows the answer but does not have instincts about where to begin (Jones, 2014). Costa and Kallick suggest that the habits of mind should be taught from early childhood, but can be learned later in life as well, and are constantly refined throughout the lifespan. This attitudinal approach to problem-solving is appropriate for all subject areas and for life in general.

4.2. Planning for problem-solving: *understanding by design*

Understanding By Design (UbD; Wiggins and McTighe, 2005) is a mental framework in which teachers and learners always begin with three simple questions: (1) What is the objective? (2) How will I evaluate? (3) What do I do? In this model, the learning begins with the end in mind: *Where do I want to be when this process is finished? How will I know I have been successful in meeting my goals?*

The first step in UbD is to identify the objective. It is a useful mental framework when clarity is needed to shed light on a problem, and to establish the "why?" behind instruction (e.g., *why learn this?, why do the assignment?; why is this important?; why meet over this topic?*), which is also known as "root cause analysis" in psychology (Okes, 2019). In a classroom setting this tends to support collaboration between teachers and students toward a co-constructed curriculum, as the overall objective of assignments is made explicit. The second step identifies the many ways people can evaluate advancement toward the objective, ensures everyone shares the same understanding of success criteria, and commits the group to one clear and transparent tool. For example, a school may have a goal of "academic excellence" but some may think excellence means high test scores, others may think it is school harmony, and yet others might think it means having a well-rounded or happy student body. Shared criteria increases the likelihood of achieving objectives (Moss, 2022). Once the objective and the evaluation tools are agreed on, the final step is to plan the activities and identify needed resources. This is a primary sticking point in education, as many schools plan activities before defining objectives and plans for assessment. When this happens, people often end up evaluating the activities rather than any progress toward the shared objective. Additional problems arise when there is a mismatch between the objective and the evaluation tools and/or activities designed, and this can impact acceptance and motivation.

UbD is a useful mental framework for problem-solving at all levels of education and can, in fact, serve as the default starting point when approaching *any* problem in need of clarification, independent of whether the actor is the student, parent, or teacher. If one begins by asking *why the problem should be solved* in the first place, this process of objective identification sets the solver in motion to follow a framework that supports effective problem-solving. Moreover, by beginning with UbD, people clarify their own biases and presumptions about the benefits of a given approach before searching for solutions. Teachers can model this approach for students as early as preschool and do so by simply incorporating a short conversation about why each new learning objective is important, how it will be measured, and how it will be learned.

4.3. Problem-solving through *design thinking*

A third framework worthy of consideration is *design thinking*. In Brenner and Uebernickle's model, Brenner and Uebernickel (2016) of design thinking there is a seven-step process. These steps begin by establishing empathy for the people who will be most affected by the new design, usually the end-user. Once empathy is established, one can then (a) define the problem, (b) determine the root causes of the problem, (c) brainstorm or develop alternative solutions, (d) select the best solution, (e) implement the solution, (f) evaluate the outcome, and (g) reassess the problem. The end result of a positive design thinking experience, according to Panke's summary Panke (2019), is to increase collaborative decision making, promote playful learning, reduce cognitive bias, create conditions for flow, foster meta-disciplinary collaboration, nurture creative confidence, induce productive failure, and increase resilience.

Design thinking has roots in engineering and business (Von Thienen et al., 2018), and combines problem-based learning with inquiry and project-based learning, to devise authentic learning experiences. Design thinking is particularly beneficial when the goal is to solve certain types of wicked problems in groups, like those associated with creating or fixing a physical object, policy, or program. While typically associated with older students, design thinking may be explicitly and implicitly used in early-years-education and might require nothing more than the props of the environment. For example, a preschool teacher can point out the difficulties of a person trying to mount the stroller over the sidewalk when there is no ramp ("Poor lady! How hard it is to get a stroller up and over that curbside!") and ask the kids what could be done about it. Panke (2019) notes that design thinking is both a process as well as a mindset, however. While great for problem solving, design thinking can also be a source of frustration or anxiety for participants unfamiliar with collaborative problem solving under design thinking conditions, which is why exposure to design thinking early in life may help reduce resistance later.

4.4. Assessment of problem situations: pairing *compass and SWOT*

The Compass activity fits within Harvard's Project Zero's "Thinking Routines" (Ritchhart and Church, 2020) and is a successful framework for assessing personal perspective on problems. The SWOT analysis method is thought to have been born in business education programs in the 1960s (Kaplan and Norton, 2008), and was embraced by industry in the 1970s (Andrews, 1971). It has been used as a problem-solving tool in education since the 2000s (AlMarwani, 2020).

Designed to facilitate self-assessment and the assessment of situations, the Compass Activity is a mental framework which asks the learner to think of the North, South, East and West as follows:

- **N**orth stands for **Needs**
- **S**outh represents **Steps** to take
- **E**ast means **Excitement**
- **W**est demonstrates the problem-solver's **Worries**

Before beginning to resolve the problem, the problem solver considers their own emotions around the steps to problem-solving, by assigning answers to what they need, what steps they should take, what they are excited about, and the worries they have. Children as young as three can be coached into self-assessment in this way, and the tool remains exactly the same for adults facing problems. Once the problem solver has decided on a resolution, they can then conduct a SWOT analysis. A SWOT analysis asks the problem solver to consider their situation based on the chosen resolution:

- What **Strengths** does this resolution provide?
- What **Weaknesses** have been created or remain?
- What **Opportunities** does this offer moving forward?
- What **Threats** can hinder true problem resolution?

Engaging in both the Compass activity and the SWOT analysis encourages the problem-solver to be both introspective, and to "zoom out" for perspective, which changes the nature of the problem (Minsky and Aron, 2021). For example, if one needs the teacher to give more help (external), the problem is different from one needing more time to do the work (internal). Similarly, if a solution exposes a weakness in leadership (external), that is different from thinking one's computing skills are weak (internal). The locus of control in approaching the problem changes, based on this internal and external assessment. Learners who habituate the Compass Activity and SWOT learn that no resolution is without its conflicts, and that those can have roots in *who* is presumed to have control over the problem resolution.

This broader mental framework helps learners identify and embrace what they are working toward and excited by, while also pinpointing the worries and threats that may accompany a successful project. Ostensibly, this framework encourages a thinker to consider their emotions while also identifying actionable steps to take, thereby explicitly connecting emotion and cognition in decision making. This model is particularly good for problems in which the learner has low motivation and needs to be reminded of the benefits of resolving the problem, as it encourages a focus on strengths and opportunities. It may be used by teachers and learners to distill a bigger problem into manageable "bite-sized" pieces in any subject area (AlMarwani, 2020).

5. Existing mental frameworks from psychology

Some mental framework examples from the field of psychology that show excellent results, but will not be discussed here include *Solution Stories* (Kelley, 2018), which are based off of Vygotsky's Social Constructivism Vygotsky (1978), Pekrun's Control Value Theory of Emotions Pekrun (2006), and Lerner's work on human development Lerner (2006); the *Monsen Problem—Solving Model* (Monsen and Frederickson, 2016); and *Cognitive Decoupling* (Koichu and Leron, 2015), which is based on hypothetical thinking, mental representations, and working memory capacity.

Three examples from psychology will be presented. We will first examine the ***Cognitive Bias Codex*** and show how it is used to problem-solve, based on types of information intake. We will then discuss how problem-solving functions as an ongoing negotiation between **challenge and threat**, and how one's self-perception as a learner influences successful problem-solving through **growth mindset** maintenance.

5.1. Constraints on perception and decision-making during problem solving: *cognitive bias codex*

Benson's Cognitive Bias Codex ("CBC"; Benson, 2016) represents an interesting mental framework to aid in teaching and learning and serves as a psychologically grounded bridge from the educational models mentioned above to newer frameworks from neuroscience, which follow. Chronological in its structure, the Cognitive Bias Codex is one way to explain that information, meaning, and time create constraints within which our brain understands the world and thereby develops heuristics and biases. Benson suggests signals are detected in the environment, whereby personally relevant meaning is assigned to them based on an individual's prior experience. Next, a decision is made, often automatically or without conscious awareness, based on that primarily subjective meaning. The result of that decision is then experienced. The memories created through this process are fed back into the system to influence subsequent iterations of this process.

While by no means the only taxonomy of bias (also see Tversky and Kahneman, 1982; Oreg and Bayazit, 2009; Gigerenzer and Gaissmaier, 2011; Korteling et al., 2018) the CBC suggests that our interaction with the world is always influenced by what we already know. What we already know (or do not yet know) may hinder problem-solving. For example, there may be too much new information with which the learner is unfamiliar. Other times problem-solving is hindered because a learner lacks meaning or context for the learning. In a third case, problem-solving may be hindered because a student has too little time to respond thoroughly. Finally, Benson suggests that in other instances, one's problem-solving skills (or lack thereof) are due to an inability to know what is important or to prioritize information. This framework suggests people are often unaware of the biases under which they perform daily routines, including problem solving, because they are driven by observable, however unconscious, heuristics grounded in prior experience.

The CBC is helpful in problem-solving when it is unclear why progress is not being made, and it can also aid a learner in identifying biases of which they were previously unaware. In a hypothetical example, let us presume there is a woman who is in charge of environmental issues at her company. She is asked by her boss to recommend priorities for the coming year.

> "Everything," she answers.
> "Yes, everything is important," responds the boss, "but what should we prioritize?"
> "Everything," she says again.
> "But what, specifically, would you recommend we give most of our budget and attention to?"
> "Everything. The environment is everything, so everything is important."
> "That's precisely why I would like your opinion. We can't do everything, so I'd like you to suggest what is most important."
> "It's all important."
> "Yes, it is all important. But where should we focus? The oceans? Plastics? Toxins? Carbon emissions?
> "Yes."
> "Which?"
> "All of them are important."

Despite being the expert on the environment in the office, with awareness of many environmental challenges, the woman is unable to prioritize them. What keeps intelligent people from being able to resolve the problem at hand (e.g., plan the budget and agenda for the coming year)? There are four primary answers, according to Benson. Sometimes the ability to resolve a problem is due to "analysis paralysis" in which too much information is presented to be processed all at once. On the CBC, this is seen as a "Too Much Information" problem (A). It is also possible the woman was unclear about what her boss needed from her. *Was this a report? A list? A budget?* She might not have had enough meaning (B) to respond. In other cases, some, but not all people with a high level of *content knowledge* and sufficient *communication skills* are familiar enough with the problems of their field that they can consider patterns of past responses and use them to approach new problems but cannot do this quickly. This may result in difficulty responding in the "Need to Act Fast" quadrant. The speed of reply is related to the familiarity of responses from the past (C). Finally, in other cases the woman might have had access to all the right information, and understood it, but was unable to prioritize it (D).

The Cognitive Bias Codex may be new to teachers but it relates to situations visible in all classrooms and all age levels. Students may be unable to resolve problems because they have too much information and do not know how to order the information (A). They may take in the information but have insufficient prior knowledge upon which to scaffold new understanding (B). Perhaps the most common problem, also identified by Benjamin Bloom in 1968, is that there is not enough time for smart students to make their way through the information, resulting in hurried answers which are insufficient (C). Finally, many students learn vast amounts of content shared in the classroom and hold it long enough to pass tests, but do not retain it all (D) for reasons ranging from a lack of authentic context, strong mental schema, or association to other prior knowledge. The CBS is a useful framework for problem-solving at all age levels, within all topics, and useful beyond the school years.

5.2. Reframing and problem solving: *challenge and threat*

The "Threat versus Challenge" outlook is a problem-solving framework for appraising life's circumstances to the benefit of performance and outcomes (Lazarus and Folkman, 1984). Learning requires a great deal of energy. Approaching problems as challenges rather than threats results in physical bodily changes, permitting the problem solver to be more efficient with their limited energy. If a student believes in their own ability to tackle a problem, however challenging, they experience fewer negative physical, emotional, and psychological outcomes (e.g., Mitchell et al., 2019; Wormwood et al., 2019). This does not mean that they are fully equipped to solve a given problem, but it does mean that with mind, brain, and body in greater balance they have more energy to recruit and access the needed resources (e.g., knowledge, skills, social support, instrumental supports) and manage stress which can otherwise interfere with thinking. By approaching problems as challenges and not as threats, the equilibrium of the student becomes a protective factor for successful, open-minded problem-solving.

Originally based on coaching models, threat versus challenge has been widely studied in athletic settings (e.g., Mitchell et al., 2019; Meijen et al., 2020). Engaging in this mental framework activates the parasympathetic nervous system, which in turn, allows the executive networks of the brain to preside over the sympathetic nervous system, thereby down-regulating and calming the limbic system (e.g., Sicorello et al., 2021). Consequently, if a student is afraid of something (danger/threat), they are more likely to retreat, but if they view it as a challenge (opportunity), they are more likely to spring into action, and seeing something as a surmountable challenge increases the likelihood of problem resolution (e.g., Lazarus and Folkman, 1984; Tomaka et al., 1993; Mitchell et al., 2019). This perspective makes room for divergent and creative thinking because the brain tends to treat challenges with approach-style responses (e.g., *What action can I take?, What do I know about this?, What help might I recruit?*), and threats with retreat or survival-oriented responses (e.g., fight/flight/freeze).

Using the challenge versus threat mental framework to resolve problems is particularly useful when approaching new or unfamiliar problems (Espedido and Searle, 2020). This approach is also supportive when the problem-solver has a previous self-perception of being "bad" at the type of problem being resolved (Buffone, 2015). This mental framework of applying a cognitive reappraisal to a problem before approaching it can have a direct impact on one's problem solving abilities (Eastcare and Greenville, 2019). Costa and Kallick suggest that approaching the world and its problems with "wonder and awe" Costa and Kallick (2009) can habituate a challenge mentality, reduce threat perception, and is a skill that can be taught to very young children, but should be rehearsed across the lifespan in as many contexts as possible.

5.3. Growth mindsets and problem-solving: *Dweck's mindsets*

A mental framework similar in premise to "challenge and threat" is that of Dweck's mindset theory (Dweck, 1999, 2006), wherein a growth mindset—one's positive belief about their own ability to grow and improve through incremental effortful action—influences [academic] outcomes. By contrast, in Dweck's model, a fixed mindset-oriented person believes that they were born being good or bad at certain elements of learning (or particular subjects) and does not see value in expending incremental effort designed to help them improve bit-by-bit (Brougham and Kashubeck-West, 2018). There is also extensive research showing that mindsets are malleable, and that a growth mindset can be improved and developed with intervention (Haimovitz and Dweck, 2017; Seaton, 2018; Zeeb et al., 2020). This explains why the internal mantra when facing a hard problem of "I cannot do it *yet*" is of such importance in growth mindset cultivation.

There is value in growth mindset training for educators and learners (Blackwell et al., 2007; Brougham and Kashubeck-West, 2018; Sarrasin et al., 2018) which relates directly to problem solving. Research on mindsets in educational settings has demonstrated that the mindset of the teacher can be as impactful (if not more so) as that of the student, in terms of a student's beliefs about their own abilities in the classroom, and ostensibly, to solve-problems (Seaton, 2018; Canning et al., 2019; Frondozo et al., 2020; Richardson et al., 2020). First, a person with a growth mindset tends to view problems as opportunities, which permits them to face challenges incrementally, rather than succumbing to a counterproductive fear of failure or overwhelm. Second, problem-solving quality is enhanced because a growth mindset offloads demands on neurological, psychological, and physiological networks permitting critical thinking to occur (Ng, 2017: Sarrasin et al., 2018). These first two points result in a shift—rather than feeling defeated and depressed by a problem, people with growth mindsets consider them as opportunities to grow.

Using the mental framework of a growth mindset for problem-solving is best used when a positive reappraisal might be helpful, or an emotional or cognitive block is getting in the way of progress. Growth mindsets can be cultivated with the youngest of children and developed throughout the lifespan. It can help a student find motivation and serves to enhance physical and mental wellbeing in learning and is often a key element in the development of resilience.

The *Cognitive Bias Codex*, *Challenge and Threat*, and Dweck's *Mindsets* serve to link the educational mental frameworks of the *16 Habits of Mind*, *Understanding By Design*, *Design Thinking*; and *Compass and SWOT* to the newer mental frameworks developed in just the past decade that come from neuroscience, which we turn to next.

6. New frameworks from mind, brain, and education

In addition to problem-solving frameworks drawn from education and psychology and used in the classroom, other learning sciences, such as neuroscience, may also offer important models. In this section we will consider the value of approaching problems from a **transdisciplinary perspective**; using **holonic thinking** to contextualize conceptual learning; employing knowledge of how the brain organizes information into the **five pillars** of symbols, patterns, order, categories and relationships; and leveraging **meaning making** strategies to make sense of context and bring authenticity to problem-solving. Each of these new mental frameworks from Mind, Brain, and Education is explained below briefly.

6.1. Perspective taking in problem solving through *transdisciplinary thinking*

Transdisciplinary thinking is an approach to problem solving that values the use of information from multiple fields. The belief is that the more, good information one has to resolve a problem, the better (Tokuhama-Espinosa, 2019). Studying domain problems like how to teach math or language, and other difficult problems in education, like student motivation, how to differentiate students based on their needs (and strengths), or ways to get children to be stewards of the environment, all require transdisciplinary thinking. It is now clear that there are few problems in the world that are better resolved using a single lens, framed only by one field of study, rather than by using multiple lenses, incorporating perspectives from various fields that "embrace the 'mess' of diversity," (Kenter et al., 2019, p. 1,439).

Transdisciplinary studies were promoted by the Romans and were popular throughout the Middle Ages reaching a height with DaVinci's Universal Man in the 1500s, which signaled the intellectual peak of integration of distinct fields like the arts and sciences. Beginning with the Industrialized Age in the late 1770s, jobs became more and more siloed and specialized (Nicholls and Murdock, 2012). Hyper-specialization was celebrated more than universal, transdisciplinary thinking throughout the 1940s and 1950s. However, the 1960s brought pushback against siloed ways of thinking, and it once again became popular to think about problem-solving using multiple lenses, with a renewed interest in transdisciplinary thinking at the forefront of debate (Jantsch, 1972).

Transdisciplinary thinking reminds problem-solvers to continually seek different perspectives and recognizes that different fields employ varying tools to measure and resolve problems (Yeh, 2019). It encourages a de-siloed approach to thinking that supports the problem-solver through a process of challenging their assumptions and considering a range of explanations, and honors the interconnected nature of everything (e.g., cognitions and emotions; genes and environments; risk and protective factors; individuals and groups, etc.). In facing the many kinds of problems that exist in the world (e.g., climate change, pandemics, poverty, war) and in the classroom (e.g., student motivation, community wellbeing, social engagement), transdisciplinary thinking asks problem-solvers to take the perspective of different field professionals to find answers. *How might an economist respond to a problem, as opposed to an environmentalist? How would a teacher respond as compared to a parent? A novice teacher compared to a master-educator? A social scientist* versus *a physicist?* By taking on different field perspectives in this way, problem-solvers are likely to identify solutions that would not be visible from a single disciplinary view (Swayne, 2020). Transdisciplinary thinking may be used in any realm to solve all types of problems and is particularly helpful in solving wicked problems and problems with several conflicting solutions.

Transdisciplinarity is challenged by the current design of education in which school is divided into subject areas. As a mental framework accessible from the earliest stages of development, it can, however, be developed by even very young children using a perspective taking approach to learning (e.g., Hodges et al., 2018) in which students are asked to play the role of different actors in problem-solving. Children can role-play various perspectives from around the age of three or four (*How would the shop keeper respond here? What would the mayor say? How would the children react?*). This can evolve from actor to disciplinary thinking (*What does biology say about this? What does philosophy propose? How would an environmentalist react?*) over time.

6.2. Problem-solving by examining all parts, macro to micro: *Holonic thinking*

An extension of transdisciplinary thinking is *holonic thinking* in problem-solving, which means appreciating that everything in the natural world can be considered a part as well as a whole (Esposito, 1976). The idea was derived from the Greek "holos" meaning whole, with the suffix "on" which, as in proton or neutron, suggests a particle or part (Edwards, 2003). A child is a whole unto themself, but she is also a part of a family, a school, a soccer team, and a classroom. A home is a single entity, but it is also part of a neighborhood, community, or town. Your brain is a whole, but it is also a part of your body. Holons can always be considered as smaller parts, or larger "wholes."

Edwards (2003) suggests that the idea of holons has been around since the Middle Ages and was used to explain the spiritual connection between all living things. *Holonic thinking* was most famously referred to in *The Ghost in the Machine* (Koestler, 1967), and in the 1990s, was introduced in engineering to make solutions to problems more agile, by changing the way each piece fit into the larger whole (Van Leeuwen and Norrie, 1997). Most recently holonic thinking has been used to explain educational practice by Tokuhama-Espinosa and colleagues, when describing how children learn to write (in review). Breaking down the complexity of writing into its smallest parts (letters, phonemes, and so on), then bringing each lesson back to a more macro level (i.e., by showing how vocabulary building, spelling, grammar lessons and other aspects of writing come together to create the whole of writing), make the process (problem) of learning to write more manageable–holonic thinking in action.

Holonic thinking might be applied to the problem of teacher education and continued professional development (Tokuhama-Espinosa and Borja, 2023). There are numerous elements to teacher education, each a world unto itself. Some focus on planning, others on evaluation, and yet others on activities, or technology, or information about how the brain learns. All of these aspects are important. Each feature of teacher education can be broken down into smaller parts as well as viewed as a part of the larger whole, and considered through the lens of what a given teacher specifically needs. It may be broken into categories of skills, knowledge, and/or attitudes or learning formats (e.g., online, in-person, ongoing versus workshop-based), and so on.

Holonic thinking can be used as a mental framework for problem-solving as holons change the perspective on the object(s) within the problems, placing a spotlight also on the *relationships* between aspects of a holon and its environment. Children as small as four or five can be asked to explain the relationships between objects (*How is the bus part of the transportation system? And how can a bus be broken down into smaller parts, like the seats and engine and windows?* Or *how are fruits part of your diet? And what are fruits made of?*). By narrowing in and scoping out, problem-solvers may use *holonic thinking* to change the main focus of the problem, consider the effects of various solutions on the holon, its parts, and those things of which it is also a part, and ultimately to resolve it.

6.3. Problems as symbols, order, patterns, categories and relationships: *five pillars of the mind*

The Five Pillars refer to the neural networks in the brain related to symbols, patterns, order, relationships and categories (Tokuhama-Espinosa, 2019) and the belief that everything a human can teach or learn has the characteristics of one or more pillars. For example, letters and numbers are symbols; analogical thinking and fractals in nature are patterns; math formulas and sentence patterns are expressions of order; cause and effect in nature as well as the stock market are relationships; parts of speech, types of emotion, and groups of fruits are all categories. The labeling of the five pillars is also interesting, as Tokuhama-Espinosa and Rivera (2013) found that children as young as three-years-old understood what "symbols," "patterns," "order," "relationships," and "categories" were.

Furthermore, Tokuhama-Espinosa and Rivera discovered that all neuroscientific studies for early math and pre-reading conducted on 0–6 year-olds could be categorized into one of these five pillars, without exception Tokuhama-Espinosa and Rivera (2013). That is, of the nearly 1,000 studies conducted on children at the time (related to math and language), all described neural networks in just these five groupings. This suggested that everything a young child learns related to language and math could be grouped as either a symbol (e.g., letters, numbers, punctuation marks, non-numerical symbols), pattern, order (e.g., sentence structure and grammar, arithmetic equations), relationship (e.g., verb-noun agreement, proportions), and/or category (e.g., word types, positive vs. negative numbers). After this initial study, the authors expanded the inquiry beyond 0–6 years-old and found that research on adult brains could also be grouped into the five pillars.

This mental framework can help in problem-solving when there are many unknowns. That is, sometimes people have problems, and they fail to understand the problem's origins. Perhaps this occurs because of narrow-band thinking, which seeks out one's best guess rather than looking for all the evidence (or considering transdisciplinary or holonic thinking). By remembering to identify the symbols, patterns, order, relationships or categories surrounding the problem, the learner may see what was before invisible and embrace the confidence to tackle the problem. For example, if a child has trouble resolving a math problem, teachers can ask them to label all symbols, then ask if they have a problem with any of them. If the problem is not due to symbols, could it be based on patterns (configurations, series, rules or regularity), the order of operations or sequences, categories or the way equivalencies are expressed, or relationships such as an understanding of the core notions of magnitude, or trouble estimating quantities? Using the five pillars as a check list can make it easier to get to the heart of the problem, which then leads to a more accurate intervention and problem resolution.

Whereas the Five Pillars are useful for reminding the learner about what he or she might not be taking into consideration when problem-solving, *Meaning Making* is a way to center the learner's experience on—and connect them to—the problem and a possible solution (Bornemann and Christen, 2020).

6.4. Sense making in problem-solving: *meaning making*

Meaning making is the process through which learners construct understanding from their own personal experiences and the information they encounter (McTighe and Silver, 2020). It is an aspect of human cognition that enables individuals to make sense of the world and confront information. Not only can it be nurtured in schools, but research also suggests this may be of particular importance for adolescents' developing brains regardless of context (Immordino-Yang and Knecht, 2020; Gotlieb et al., 2022). Evidence suggests that during adolescence, more efficient communication between brain regions supports a surge in higher-level cognitive abilities, which encourages personal, cultural, and emotional meaning-making (Immordino-Yang and Knecht, 2020).

Neuroimaging adds to our understanding of how students make meaning by identifying distinct combinations of neural networks that are employed, as the individual recalls autobiographical information (Sotgiu and Sotgiu, 2021), contrasting it with new information (Ruthven, 2019) that may be charged with emotions (Immordino-Yang and Yang, 2017). fMRI studies of adolescents show coordinated activation of specific neural networks (default mode and salience networks) when individuals watch stories that are emotionally meaningful and personally relevant (Immordino-Yang and Knecht, 2020). This finding suggests that individuals make meaning through both cognitive and emotional approaches, together.

Schools can support meaning making through problem-based learning that leverages student interest, inviting a wider range of concepts, skills, and questions that are personally relevant (Immordino-Yang and Knecht, 2020). Educational practices can support dispositions of mind that encourage the development of meaning-making skills (Immordino-Yang and Knecht, 2020). Overall, meaning making provides an effective mental framework for problem-solving by encouraging reflection, metacognition, and an adaptive, flexible approach, which supports individuals in generating more effective, innovative solutions to novel and complex problems.

As a mental framework, meaning making is an active, reflective process of sensemaking, that simultaneously draws from prior knowledge, emotions, and experiences to construct insights and meaning (Küçüktaş and St Jacques, 2022). Because meaning making involves a high level of reflection and metacognition, it may be used in problem-solving to identify gaps in understanding of others' thinking or feeling or of one's own (Jordan, 2011), and to innovate. Perhaps this encourages a more holistic approach to problem-solving, where students learn to consider multiple perspectives (and a wider range of them) in developing comprehensive solutions to problems.

Transdisciplinary Thinking, *Holonic Thinking*, the *Five Pillars*, and *Meaning Making* are newer mental frameworks that may be employed by teachers to increase the tools in students' problem solving, adaptive toolboxes. Along with those shared from education and psychology, they offer the ability to resolve almost any problem one might encounter. We end this section by acknowledging the incomplete nature of the Theory of Frameworks which has yet to be placed within a practical Taxonomy that might facilitate its use.

7. The theory of mental frameworks: a taxonomy for problem-solving?

We propose that the *Theory of Mental Frameworks* would best be expressed as a systems theory, an attempt at addressing and perhaps guiding the complex adaptive system that is the embodied human mind. One tool used in systems theories is that of a taxonomy. Building a taxonomy to organize the mental frameworks is an ongoing process and is beyond the scope of this paper. To further develop this Theory, we will need to generate core competencies, otherwise known as the combination of knowledge, skills and attitudes (OECD, 1997). These will allow us to structure the information in a way that makes the *Theory of Mental Frameworks* practically applicable to all teachers. Some of the competencies needed are summarized in Figure 1.

We acknowledge that ideally, such a tool would capture "all" mental frameworks from education, psychology and neuroscience— a welcome resource for teachers, as taxonomies often serve to succinctly organize knowledge about particular domains and establish common understandings among peers (Unterkalmsteiner and Adbeen, 2023). Perhaps this theory would be best represented as a cyclical taxonomy in which users could select from multiple mental frameworks based on problem-solving needs. Unlike Bloom's Taxonomy, the content of the mental frameworks are not single words or concepts, which invites speculation as to whether an ontology—a related but distinct approach to classification—might make more sense. Ontology is a set of concepts and categories in a subject area or domain that shows their properties and the relations between them (Oxford, 2023). This is an on-going process for the authors, which we acknowledge renders the explanation in this paper somewhat incomplete, as we believe the goal of a new theory should be in part to create useable knowledge (Connell et al., 2012).

8. Discussion

The factors that positively influence human well-being, resilience, and therefore one's ability to learn and solve problems, informed our process for contemplating which problem-solving frameworks from certain silos to include in the Theory. Specifically, Masten's research on resilience—which is itself a transdisciplinary area of study—was influential (e.g., Masten, 2001, 2011, 2019). She called resilience "ordinary magic," which is perhaps also an apt description for mental frameworks at work in problem-solving Masten (2001). It is indeed magical to witness a student encounter dissonance, cogitate, determine where they need support or additional knowledge, and then through a moment of effortful thinking or insight, sail through a complicated or wicked problem to a viable solution, and it often happens below the level of conscious awareness (Stuyck et al., 2022). And though it is magical, it is not rare.

It is our goal through this Theory, at least in part, to make this process visible and teachable. So, if resilience in the face of adversity or stress is defined as one's ability to positively adapt, to "recover," "sustain oneself," or "beat the odds" (Masten, 2001), then perhaps the science of resilience also holds lessons for how to teach the science of thinking and problem-solving, and this deserves more attention beyond the scope of this inquiry. Importantly, studying resilience, and ostensibly problem-solving, through a developmental lens "..may identify windows of opportunity when there is greater plasticity and leverage for change, so that interventions can be effectively tailored and timed for efficacy, adapted to individual, developmental and situational differences" (Masten, 2019, p. 102), an important consideration for applying the *Theory of Mental Frameworks* at different ages and stages during a child's schooling, and when faced with different kinds of problems.

Because the authors have adopted the medical oath to "do no harm" in this work, and are heavily guided by this value, it must be noted that the *Theory of Mental Frameworks* deserves extensive additional scrutiny and testing, and likely has many limitations (Miles, 2004). Though it is built upon evidence from each of the MBE fields, and contemplates historical perspectives, it is an unproven and hypothetical proposal. The authors look forward to engaging in debate with others who research problem-solving in this context. The research leading to this Theory generated at least five important points of discussion.

8.1. Teachers cannot teach what they do not yet know

The development of critical thinking and problem-solving skills requires effective teaching of mental frameworks to underpin them. To teach critical thinking for problem-solving effectively, the teacher must be familiar with the various mental frameworks that are involved in the processes (Thomas and Lok, 2015). Contrary to intuition, teaching one mental framework is not enough, as not all are effective or ideal for all problems or people. Unfamiliarity with mental frameworks will handicap teacher instruction of them as one cannot teach what one does not yet know. Therefore, while equipping students with a range of options may improve the likelihood that they can access an appropriate framework in context, doing so may require extensive repetition to execute, and require intensive teacher training.

While teachers know and use many of the models presented here individually, few may have used multiple frameworks in concert or applied them interchangeably (Hmelo-Silver, 2004). Teachers who value the flexibility of multiple models will be able to

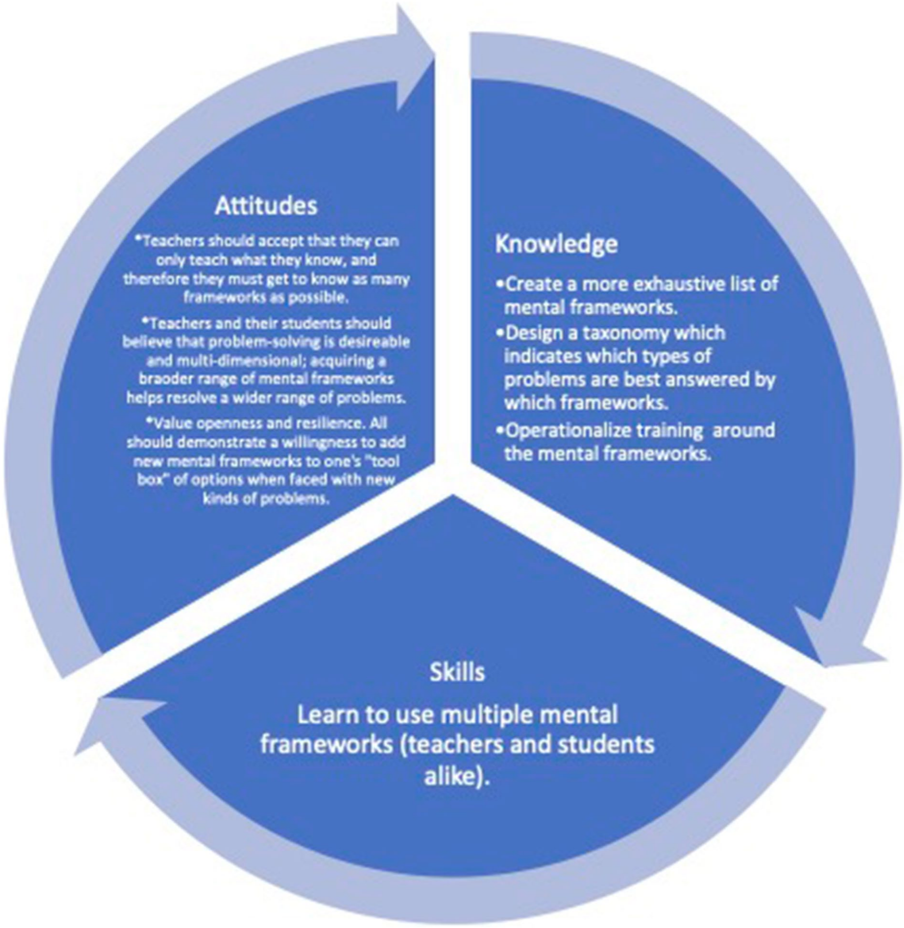

FIGURE 1
Steps to move from theory to practice.

model this for their students, while teachers who are unaware may place their students at a disadvantage. Having a range of mental frameworks at their disposal may also aid students in their ability to pivot quickly and adopt a new approach if the first framework is unsuccessful. To achieve this, students need to understand the various cognitive processes involved in critical thinking for problem-solving, including the heuristics and biases that may be present in any mental model, which in some scenarios may occur without their awareness. This kind of higher order thinking can only be developed with guidance by someone more knowledgeable (Hamzah et al., 2022). Without a deep understanding of these elements, teachers' efforts to develop them in their students may be less effective.

What is more, decoupling the problem-solving process from the typical product, or correct answer, involves disrupting complex heuristics which are hard to remediate in the world of high stakes testing (Jones et al., 2003). Teachers who mistakenly equate higher order thinking with test scores may consider time spent on cultivating multiple frameworks for problem-solving in their students unproductive. To ensure that teachers are equipped with the necessary knowledge, skills, and attitudes to effectively teach critical thinking for problem-solving, it is important to prioritize their own knowledge of and familiarity with these frameworks (Thomas and Lok, 2015). This includes not only providing educators with ample opportunities for professional development (Franco and Vieira, 2019; Celik, 2021), but also ensuring they have access to high-quality resources and support. Notably, the development of these thinking skills is an ongoing process, beginning with initial exposure to the ideas, developing into an understanding of how and to what extent the frameworks may be helpful, and eventually using them heuristically as effective complex problem-solving strategies. And as with any new learning, the learning characteristics of the teacher-as-learner will also impact their ability to upskill in this area.

8.2. Flexible thinking via executive functions

In order to apply mental frameworks both teachers and students must be agile and willing. Cognitive flexibility is an executive function that enables individuals to adjust their thoughts and behaviors to meet changing situational demands and has been identified as a necessary skill for personal and professional success in the 21st century (Diamond, 2013; Saleh, 2019; Van Laar et al., 2020; González-Pérez and Ramírez-Montoya, 2022). In an educational context, flexible thinking enables learners to transfer knowledge to new situations, adapt to different learning environments, and find novel solutions (Diamond, 2013). Adaptability is considered a facet of flexible thinking, as it enables learners to engage with new contexts and problems in an efficient manner (Barak and Levenberg, 2016). Adaptable, flexible thinkers are able to approach novel and complex problems effectively, in part because they are able to utilize relevant prior knowledge and transfer (or generalize) it to new situations (Bransford et al., 2000).

Cognitive flexibility is a multifaceted construct with varying components that include set-shifting, task-switching (Miyake et al., 2000; Dajani and Uddin, 2015), and cognitive inhibition (Diamond, 2013). Research has demonstrated the importance of flexible thinking in academic contexts (Blair and Razza, 2007; Diamond and Lee, 2011; Diamond, 2013). Influential work by Blair and Razza (2007) identified cognitive flexibility as a significant predictor of early academic achievement in math and reading and found it also predicted later academic achievement in reading, math and science. These findings suggest that flexible thinking is a crucial skill for success in academic domains as well as in daily life. Therefore, it should be developed as an essential element of one's education. Research has identified several effective strategies for promoting flexible thinking skills in school-age children, Blair and Razza (2007), Diamond and Lee (2011), Diamond (2013) which have the potential to also improve academic outcomes.

Flexible thinking and the efficient use of mental frameworks can support one another reciprocally. The more knowledge and familiarity one has of these models, the more mental flexibility one might demonstrate in considering, selecting, and applying them to suit a particular context. Similarly, greater flexibility in thinking might also help an individual contemplate numerous frameworks from various perspectives and become a heuristic practice unto itself. Flexible thinking is a crucial executive function that enables individuals to adapt to changing situational demands and solve complex problems, and it is embedded in each of the frameworks themselves. Moreover, it is central to the working theory contemplated herein.

8.3. Critical thinking and problem based learning

In addition to cognitive dexterity, critical thinking is worthy of attention in this discussion. While many teachers are very familiar with the term, and may have experimented with it, few have experience in habituating mental frameworks. One approach to developing critical thinking and problem-solving skills in students is problem-based learning (PBL). PBL was originally developed in the 1960's as a way for professors to help medical students who were struggling to retain information for application in clinical practice (Thorndahl and Stentoft, 2020). These students were missing the reasoning skills that more experienced physicians possessed (Hmelo and Cote, 1996), so PBL was created as a way to support ongoing learning in professional practice (Boud and Feletti, 1997). A scoping review by Thorndahl and Stentoft (2020) found that PBL rapidly spread through higher education in the U.S. and Europe, with numerous universities promoting it to enhance critical thinking skills. The researchers explain that critical thinking and PBL are therefore closely intertwined and are supported by the efficient use of mental frameworks.

While there are numerous applications of PBL, at its core, it involves students working collaboratively to solve or answer complex problems and questions, using their prior knowledge and developing new understandings in the process (Kokotsaki et al., 2016). Through engagement with authentic problems and challenges, students are encouraged to analyze, evaluate, and synthesize information to generate and test possible solutions (Ahlam and Gaber, 2014). This process not only helps students to develop critical thinking skills, but also enhances their ability to transfer these skills to new situations (Savery, 2006). However, as critical thinking is not an innate ability, but rather a set of skills that is developed over time, it is important that educators support students directly in cultivating these skills (Savery, 2006). Teachers can support PBL with explicit instruction of strategies to approach problem solving, including a variety of mental frameworks that will serve students in and beyond the classroom.

8.4. Novice to expert

A fourth reflection considers the relationship between mental frameworks and one's stage as problem-solver (novice to expert). The Dreyfus Model of Skill Acquisition outlined a series of stages through which a learner passes as they go from a beginner or novice, originally knowing nothing about the material or skills at hand, to becoming an expert (e.g., novice, advanced beginner, competent, proficient, and expert; Dreyfus and Dreyfus, 1980; Peña, 2010). Ostensibly, as a person practices they become more competent and along with this competence comes the ability to change and manipulate processes or concepts—they can even be more cognitively flexible and creative (Peskin and Ellenbogen, 2019; Teng et al., 2022). Later adapted by Benner (1982) into the *Novice to Expert* model, it was used for nurse practitioner training. The idea has subsequently been applied outside of medical training spaces and the broader concept is underscored by findings in neuroscience related to neuroplasticity, and how the brain moves from relying on a heavy cognitive consumption when learning something new, to a lower cognitive load as something learned becomes practiced and eventually automated (e.g., Pezzulo et al., 2010; Debarnot et al., 2014; Peskin and Ellenbogen, 2019). Again, we see the important role of heuristics emerge.

In education, a learner progresses from novice to mastery ability, then gains the agility to apply the newly adopted skills, thereby changing their approach to future learning as the process progresses, in what might be described as an upward spiral of learning (e.g., Baynouna Al Ketbi, 2018; Teng et al., 2022). Novice problem-solvers are likely to have fewer strategies for tackling challenges, whereas experts may flow freely and flexibly between approaches.

Learning new mental frameworks might therefore require more effort for novices before becoming effortless or automatic, and teachers can learn to coach students through the stages with patience and persistence, to the benefit of greater learning. Practicing new mental models will support future learning for students who will be experts in their ability to pull from a wider range of thought and problem-solving modes, eventually.

8.5. Frameworks alone are not enough

Finally, while having access to mental frameworks will benefit learners by growing their toolbox of options, tools and frameworks alone are not enough. In most senses, less is not more in the world of learning. Indeed, there is much evidence across fields of learning science supporting the idea that more is better in education—more tools, exposure, experiences, practice, channels of delivery, perspectives, skills, knowledge, and of course, mental frameworks. They each contribute to improved mental agility and innovation. As professor of neuroscience, Klemm (2012) reinforced, "the more you know, the more you can know," and the more mechanisms one will have for tackling more complex problems and solving new ones in the future (Batchelor et al., 2021). What there is not more of, however, is time. It is ironic that problem-solving around the role and nature of schools in society points to the formation of problem solvers themselves, and that implementing a tool that may facilitate this, such as the Theory of Mental Frameworks, requires time to learn.

Currently, many schools find it necessary to prioritize what can easily be measured (Tokuhama-Espinosa, 2014). Straight-forward, quantifiable multiple-choice tests require less time than tracking the development of each child's mental frameworks. Operationalizing the *Theory of Mental Frameworks* has the potential to meaningfully improve how we teach critical thinking and problem-solving for all types of learners in all types of contexts, as it leverages neuroplasticity to curate vital heuristics that support everything from emotional and cognitive dexterity to executive functions, meaning making, transdisciplinary and holonic thinking, and ultimately, the ability to address wicked problems. But it will take time. This observation suggests that learning about mental frameworks should begin in the earliest school years and be a lifelong pursuit, as problem-solving is a human skill needed at all age levels.

Broadly speaking, we feel teaching based upon the *Theory of Mental Frameworks* will encourage cognitive exploration that: (a) is less linear and predictable in its duration for each student, (b) is less concrete at the outset in determining what the "right" answer(s) to a problem may be, (c) assumes that there are multiple viable approaches and solutions to most problems, and (d) is transferrable to other life contexts. In conclusion, we propose that the *Theory of Mental Frameworks* offers a reliable, transdisciplinary, meta-process for extending adaptive toolkits to approach problems with greater flexibility, adaptability, and with the dexterity to pivot when different approaches are needed.

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

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

Acknowledgments

The authors wish to thank people who have offered feedback on various versions of this paper between 2013 and 2023.

Conflict of interest

Authors TT-E and CB have received payment from Connections: The Learning Sciences Platform for administering teaching courses. Author CB is employed by The Decision Lab.

The remaining 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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frontiers | Frontiers in Psychology

TYPE Original Research
PUBLISHED 26 July 2023
DOI 10.3389/fpsyg.2023.1181989

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OPEN ACCESS

EDITED BY
Amy Corrinne Roberts,
University of Wyoming, United States

REVIEWED BY
Leilei Mei,
South China Normal University, China
Din-yuang Huang,
Fu Jen Catholic University, Taiwan
Sheilla Magbanua Trajera,
University of St. La Salle, Philippines

*CORRESPONDENCE
Yapeng Wang
✉ wangya_peng@163.com

RECEIVED 08 March 2023
ACCEPTED 10 July 2023
PUBLISHED 26 July 2023

CITATION
Lu D, Wang X, Wei Y, Cui Y and Wang Y (2023) Neural pathways of attitudes toward foreign languages predict academic performance. *Front. Psychol.* 14:1181989.
doi: 10.3389/fpsyg.2023.1181989

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Neural pathways of attitudes toward foreign languages predict academic performance

Di Lu[1,2], Xin Wang[1], Yaozhen Wei[1], Yue Cui[1] and Yapeng Wang[1]*

[1]State Key Laboratory of Cognitive Neuroscience and Learning and IDG/McGovern Institute for Brain Research, Beijing Normal University, Beijing, China, [2]School of Psychological and Cognitive Sciences and Beijing Key Laboratory of Behavior and Mental Health, Peking University, Beijing, China

Learning attitude is thought to impact students' academic achievement and success, but the underlying neurocognitive mechanisms of learning attitudes remain unclear. The purpose of the present study was to investigate the neural markers linked to attitudes toward foreign languages and how they contribute to foreign-language performance. Forty-one Chinese speakers who hold differentiated foreign language (English) attitudes were asked to complete an English semantic judgment task during a functional magnetic resonance imaging (fMRI) experiment. Multimethod brain imaging analyses showed that, compared with the positive attitude group (PAG), the negative attitude group (NAG) showed increased brain activation in the left STG and functional connectivity between the left STG and the right precentral gyrus (PCG), as well as changed functional segregation and integration of brain networks under the English reading task, after controlling for English reading scores. Mediation analysis further revealed that left STG activity and STG-PCG connectivity mediated the relationships between English attitudes and English reading performance. Taken together, these findings suggest that objective neural markers related to subjective foreign language attitudes (FLAs) exist and that attitude-related neural pathways play important roles in determining students' academic performance. Our findings provide new insights into the neurobiological mechanisms by which attitudes regulate academic performance.

KEYWORDS

foreign language attitudes, academic performance, fMRI, functional connectivity, graph theory

1. Introduction

Attitude is generally defined as a person's evaluation toward a(n) entity, object, target, or subject matter on a negative to positive (or favorable to unfavorable) continuum (Gjicali and Lipnevich, 2021), and it is a critical factor in predicting individual academic achievement (Credé and Kuncel, 2008). Appropriate attitudes are widely believed to maximize ability and consequently optimize results (Gardner, 1985; Anderman and Wolters, 2006; Oroujlou and Vahedi, 2011). At the behavioral level, evidence has shown that academic attitudes are closely related to academic success across domains, such as reading, math, and science (Masgoret and Gardner, 2003; Chen et al., 2018; Demir-Lira et al., 2019; Gjicali and Lipnevich, 2021). Moreover, a positive attitude is usually associated with good academic performance, whereas a negative attitude often correlates with poor academic outcomes (Masgoret and Gardner, 2003; Demir-Lira et al., 2019; Gjicali and Lipnevich, 2021).

For foreign language (or second language, L2) learning, learners' attitudes also play important roles. Accumulating evidence from cross-sectional studies shows that learners' attitudes toward foreign languages are closely related to individual foreign language proficiency, achievement, and other performance (Merisuo-Storm, 2007; Oroujlou and Vahedi, 2011). Importantly, a meta-analysis involving 10,489 individuals demonstrated a significant positive correlation between attitudes toward language learning and second language achievement (Masgoret and Gardner, 2003), and evidence from longitudinal studies further confirmed that positive foreign language attitude (FLA) accounts for the most variance in L2 reading comprehension (Kozaki and Ross, 2011; Smith et al., 2017) and the growth of oral proficiency (HernÁNdez, 2010). More importantly, studies of various age groups (e.g., school-aged children and adults) and sociocultural backgrounds (e.g., Western culture and Eastern culture) support this stable correlation between FLA and academic performance (Masgoret and Gardner, 2003), irrespective of the script of the target language (alphabetic or graphic). That is, the closed relationship between FLA and academic performance is age- and culture-independent.

Explanations for these behavioral findings vary. For example, Merisuo-Storm (2007) argued that negative attitudes toward language learning can reduce learners' motivation and harm language learning, whereas positive attitudes can do the opposite. Similarly, Oroujlou and Vahedi (2011) supposed that students hold general positive attitudes and beliefs that are reflected in positive emotions in learning and greater persistence, whereas the negative attitudes accompanied by passive feelings inhibit students' interest and determination to perceive knowledge (Oroujlou and Vahedi, 2011).

However, these explanations might simplify the relationships between attitudes and behavior. First, attitude is a psychological tendency that is expressed by evaluating a particular entity with some degree of favor or disfavor (Eagly and Chaiken, 1993), and it includes a cognitive component (learners' evaluative beliefs), an affective component (learners' feelings and emotions regarding the object to be learned), and a conative component (learners' action readiness and behavioral intentions; Fishbein et al., 1977; Sardegna et al., 2018). Second, attitude often intermixes or interacts with other psychological constructs, such as belief (self-efficacy), emotion (anxiety and enjoyment), and motivation (Masgoret and Gardner, 2003; Oroujlou and Vahedi, 2011; Saito et al., 2018; Sardegna et al., 2018). Third, the roles of attitude in regulating attainment might be antecedent, outcome, and mediating or moderating variable(s) (Asakawa and Oller, 1977). In this sense, clarifying the potential interaction mechanisms between FLA and L2 performance purely based on behavioral studies is difficult.

Crucially, despite decades of behavioral studies, the underlying neural pathways that can explain the effects of learning attitudes on learning performance have yet to be identified. To our knowledge, only three studies in the domain of mathematics have explored the neurocognitive mechanisms of math attitudes to date (Chen et al., 2018; Demir-Lira et al., 2019; Suarez-Pellicioni et al., 2021).

In a pioneering study related to the neurocognitive mechanisms of math attitude, Chen et al. (2018) investigated the neural mechanisms underlying the link between positive attitude and academic achievement in 6–11-year-old children who solved single-digit additions. Specifically, they tested competing hypotheses regarding the differential roles of affective-motivational and learning-memory systems and found that a positive attitude was associated with increased hippocampal learning-memory system engagement, but it was not associated with an enhanced response in the amygdala and ventral striatum. Notably, the increased hippocampal response during numerical tasks observed in their study mediated the relationship between positive attitude and efficient problem solving, leading to academic success in children.

In a second study focused on math attitudes, Demir-Lira et al. (2019) investigated the effects of the interaction between math skill and math attitudes on the neurocognitive basis of arithmetic processing (single-digit multiplication) in 8–15-year-old children. They observed that positive math attitudes were correlated with less activation in the left IFG. Moreover, they found that the relationship between math attitudes and the neural basis of multiplication varied depending on math skill. Positive math attitudes were associated with a greater activation of the left IFG only among children with lower math skills. They interpreted the greater left IFG activation as reflecting effort invested in problem solving.

In a third study of math attitudes, Suarez-Pellicioni et al. (2021) longitudinally followed some of the participants in Demir-Lira et al. (2019) study to examine the neurocognitive mechanisms underlying math attitudes and math improvement. They found that for improvers, more positive math attitudes were related to greater left IFG activation, but this effect was not identified in nonimprovers. They proposed that greater left IFG activation was associated with the investment of effort and represented the neurocognitive mechanisms by which positive math attitudes lead to improvement in multiplication skill over time. Taken together, these findings suggest that learning attitudes might function by modulating the activation of domain-general learning-memory systems or effort-related brain regions during mathematical processing. Although these studies of math attitudes provide some insights for understanding the neurocognitive mechanisms of academic attitudes, no study has directly investigated the neural basis related to foreign language attitudes. Unlike math attitudes, attitudes toward foreign language might be more complex and are related to a learner's preferences for the subject (foreign language or L2) or the associated culture (Wright, 2006; Sakuragi, 2008).

The current study aimed to examine the underlying neural markers and pathways of FLA and how they contribute to language performance during a foreign language (English) reading task. To investigate these questions, we used functional magnetic resonance imaging (fMRI) to study a sample of Chinese college students who learned English as a foreign language (EFL) when they performed an English semantic judgment task. It is well known that both L1 and L2 (foreign language) reading recruited the dorsal and ventral networks (Oliver et al., 2017; Verhoeven et al., 2019). The dorsal network includes the parietal lobe, superior temporal gyrus (STG), and inferior frontal gyrus (IFG), and the ventral one includes the occipital-temporal (vOT) and anterior IFG regions. The former is thought to subserve phonological processing, and the latter supports mapping of orthographic-lexical stimuli onto semantic representations (Oliver et al., 2017). To explore neural markers of FLA, we first applied brain activation and seed-based functional connectivity analyses to investigate differences between students with positive and negative FLA after controlling for behavioral performance. We then further employed a complex brain network analysis based on graph theory to characterize topological differences between the two groups (Bullmore and Sporns, 2009, 2012). If potential neural markers related to FLA were identified, we expected to observe differences in brain activation and functional connectivity between the two groups. At the whole-brain network level, we also expected that positive attitudes might enhance brain network efficiency during foreign language processing.

To examine the potential neural pathways by which FLA contribute to language performance, we further conducted a mediation analysis to identify whether brain activation and functional connectivity mediate the relationship between attitudes and foreign language performance. Previous work on math attitudes demonstrated that the effects between positive math attitudes and math achievement are mediated by memory strategy and greater hippocampal activation (Chen et al., 2018). Therefore, we expected that the brain's activation and functional connectivity also constitute the link between attitudes and foreign language achievement. Exploring the neural substrates of FLA can not only help us determine attitude-related effects in the specific domain but also expand our understanding of the domain-general or domain-specific mechanisms of learning attitudes This exploration will provide important insights for understanding the fundamental mechanisms of attitudes toward foreign languages and their association with language achievement and other performances, which might help us develop proper interventions to increase the efficiency of foreign language teaching and inspire learners' potentials.

2. Methods

2.1. Participants

Forty-one college students (20 females, average age = 18.46 ± 0.75 years) were enrolled in the study. All participants were native speakers of Chinese and began to learn English as a second language starting in the first grade of primary school (age of acquisition = 6.02 ± 1.59 years). They all came from Beijing and had highly similar second language education backgrounds. All participants were healthy, right-handed and had normal or corrected-to-normal vision (Yuan et al., 2021; Li et al., 2023). All participants signed an informed consent form before the experiment, which was approved by the Institutional Review Board of Beijing Normal University.

2.2. Behavioral tests

2.2.1. Foreign language attitudes

To qualify the participants' attitudes toward foreign languages, we used the Attitudes Toward English Learning Scale (ATELS; Pae and Shin, 2011), an eight-item self-assessment questionnaire aimed to measure learners' attitudes toward a foreign language (e.g., I truly enjoy learning English). The participants were asked to evaluate how much they agreed or disagreed with each item using a five-point scale (from 1-strongly disagree to 5-strongly agree). The Cronbach's alpha of the scale is 0.87. The total score of the ATELS was regarded as an indicator of learners' FLA, and all participants were divided into the positive FLA group and negative group based on the median ATELS. The two groups did not differ significantly in age, sex, IQ, age of acquisition, or L1 proficiency (see Table 1).

2.2.2. Reading fluency test

English reading performance was assessed using the reading fluency test (RFT) of the Woodcock Johnson-III (Woodcock et al., 2001), which has been widely used to probe English reading fluency and ability in previous studies (August et al., 2006; Francis et al., 2006). The test consists of 98 items that evaluate learners' general English reading ability, especially reading fluency (e.g., you can eat an apple). The participants were asked to judge whether the meaning of each English sentence was reasonable, and the total RFT score was used as the indicator of a learner's reading fluency (see Table 1 for more details on demographics and behavioral performances).

TABLE 1 Demographics and task performance of the two groups.

	Positive group	Negative group	*p* value
N	19	22	/
Gender (male/female)	9/10	12/10	/
Age (years)	18.21 ± 0.42	18.68 ± 0.89	0.065
Raven score	56.05 ± 2.30	56.50 ± 2.35	0.401
AoA	5.79 ± 1.48	6.23 ± 1.69	0.39
English attitude	32.42 ± 3.89	23.77 ± 2.72	< 0.001***
Chinese reading score	50.74 ± 10.18	44.50 ± 10.84	0.06
English reading score	81.42 ± 16.74	62.82 ± 20.78	0.003**
Semantic task_ACC(%)	0.66 ± 0.13	0.53 ± 0.15	0.006**
Semantic task_RT(ms)	1022.95 ± 59.07	1027.41 ± 73.14	0.83

N, number of participants; AoA, age of acquisition for the second language; ACC, accuracy; RT, response time. $^{**}p < 0.01$, $^{***}p < 0.001$.

2.3. fMRI experimental procedure

The participants performed an English semantic judgment task in the scanner, in which they were asked to decide whether two visually presented English words were semantically related or not. All words were 4–6 letters long (mean = 4.4). An arrow direction judgment task was used as a control task, in which the participants were asked to judge whether the arrow was pointing upward or downward, and both the experimental task and the control task were successfully used in a previous study (Tan et al., 2011). A block design was used, in which the semantic task was alternated with the baseline task (arrow direction judgment). Each experimental block consisted of 12 trials, whereas each baseline block consisted of eight trials. In each trial, stimuli (word pairs or an arrow) in white were displayed on a black background for 1,500 ms, followed by a 500 ms fixation interval. The participants were instructed to press a yes button for semantically related word pairs (or an upward arrow) using their right index finger or press a no button with the right middle finger for semantically unrelated word pairs (or a downward arrow). Half of the word pairs were semantically related, and half were not. The participants were asked to perform the task as quickly and accurately as possible.

2.4. MRI acquisition

All images were acquired using a 3 T Siemens Trio Scanner at Beijing Normal University. An echo planar imaging (EPI) sequence was used for functional imaging with the following parameters: TR = 2,500 ms, TE = 30 ms, flip angle = 90°, and scan order = interleaved. Matrix size = 64 × 64, slice thickness = 3 mm, and voxel size = 3 mm × 3 mm × 3 mm. Additionally, a high-resolution T1-weighted 3D image (MPRAGE) was acquired with the following parameters: TR = 2,530 ms, TE = 3.39 ms, flip = 7°, matrix size = 256 × 256, slice thickness = 1 mm, and voxel size = 1 mm × 1 mm × 1 mm.

2.5. fMRI data analysis

2.5.1. Whole-brain activation analysis

SPM 12 was used for image preprocessing and statistical analysis.[1] Functional images were first corrected for slice acquisition delays and realigned to the first image of the first run to correct for head movements. The images were further spatially realigned and coregistered to their corresponding anatomical images. The resultant images were then spatially normalized to the Montreal Neurological Institute (MNI) space. After normalization, all images were resampled into 3 mm × 3 mm × 3 mm voxel sizes and further spatially smoothed using a Gaussian kernel with 8 mm full width at half maximum (FWHM). An individual participant's activation t map was generated using the general linear model, in which time series were convolved with the canonical hemodynamic response function and were high-pass-filtered at 128 s.

The individual contrast images of the semantic judgment minus arrow judgment were computed as a first-level analysis, and the contrast maps were then subjected to a second-level analysis to compare activation differences between the positive and negative groups by performing two-sample *t* tests. An FWE-corrected cluster-level threshold of $p = 0.05$ (defined using a voxel-level threshold of $p = 0.001$) was applied to all whole-brain statistical maps to assess brain activations.

2.5.2. Functional connectivity analysis

We performed seed-to-voxel analysis to identify differences in the functional connectivity among the clusters identified through the activation analysis and other regions between the positive FLA group and the negative group. To this end, seed ROIs were created using the clusters that were significantly related to FLA. Using the DPABI toolbox v4.2 (http://rfmri.org/dpabi; Yan et al., 2016), we first averaged the time series of all voxels in each seed. We then temporally correlated the seed ROIs and all the other voxels in the brain, and participant-level correlation maps were obtained. For standardization purposes, the correlation maps were normalized to *z* maps. At the group level, we conducted a two-sample *t* test between group *z* maps to detect the association between FC and FLA, with English reading score as a controlling variable. Functional connectivity maps survived a corrected cluster-level threshold of $p < 0.001$ (single voxel $p < 0.001$, and a minimum cluster size of 50 voxels) using the Gaussian random field approach (Worsley et al., 1992).

2.5.3. Graph theoretical analysis

2.5.3.1. Network construction

The graph theoretical analysis was performed using the GRETNA toolbox (graph theoretical network analysis: http://www.nitrc.org/projects/gretna; Wang et al., 2015). Based on the automated anatomical labeling (AAL) atlas with 90 ROIs, we extracted the time series for each AAL ROI by calculating the mean (across voxels) signal for each time point, and a 90 × 90 Pearson correlation matrix was created for each participant for the semantic judgment condition. We constructed binary undirected functional networks using a sparsity threshold (5% ≤ sparsity ≤50%, interval = 5%) to comprehensively estimate topological properties covering a wide range of sparsity and remove spurious edges as much as possible.

2.5.3.2. Network properties and group comparisons

We calculated graph properties characterizing the global-level network organization for each participant, including the following: (1) functional segregation, which is the ability for specialized processing within densely interconnected groups of brain regions, including the metrics of local efficiency and clustering coefficient (Bullmore and Sporns, 2009, 2012); (2) functional integration, which refers to the capacity of the network to rapidly combine specialized information from distributed brain regions and includes the metrics of characteristic path length and global efficiency (Bullmore and Sporns, 2009, 2012); and (3) small-worldness, which reflects an optimal balance of functional integration and segregation (Bullmore and Sporns, 2009, 2012). To examine the group differences of all the network metrics mentioned above, ANCOVA was used for between-subject comparisons and regressed-out covariates of English reading fluency. To correct for multiple comparisons, we used a Bonferroni corrected threshold at a significance level of 0.05.

2.5.4. Brain-behavior mediation analysis

For brain activation and functional connectivity showing a significant association with FLA, we used mediation analysis to examine whether neural correlates of FLA mediate the association between behavioral FLA and English reading performance. Mediation analysis was conducted using the PROCESS macro in SPSS (Hayes, 2013).

During mediation analysis, FLA and English reading fluency were defined as the independent (predictor) variable and dependent (outcome) variable, respectively. We defined the mediator variables based on the brain statistical maps resulting from the group differences in activation and seed-based connectivity analysis described above. The significance of the indirect effect was determined using a bootstrapping method with 5,000 iterations. If a 95% confidence interval (CI) did not contain zero, then the indirect effect was significant (Preacher and Kelley, 2011; Hayes, 2013).

3. Results

3.1. Behavioral results: FLA predicted foreign language performance

To reveal the relationships between FLA and English reading performance, we correlated individuals' FLAs with English reading scores. The results showed a significant positive correlation between FLA and English reading proficiency (fluency; $r = 0.34$, $p < 0.001$). Critically, the association between FLA and language performance remained significant after adjusting for age and IQ in a multiple regression analysis.

3.2. fMRI results

3.2.1. FLA-related activation differences

First, we performed a univariate analysis to investigate group differences during English semantic decisions. After controlling for

1 http://www.fil.ion.ucl.ac.uk/spm

English reading scores, the two-sample *t* test of the whole-brain analysis revealed that, compared with the positive attitude group (PAG), the negative attitude group (NAG) showed increased activation in the left STG (BA 48, MNI: −54, −21, 6; $p < 0.05$, clusterwise FWE corrected; cluster size = 40 voxels). Relative to NAG, we failed to find stronger brain activation in the PAG (Figure 1).

3.2.2. FLA-related functional connectivity differences

Since a significant between-group activity difference was identified in the left STG, the left STG was taken as a seed region to compare the seed-to-voxel functional connectivity differences between PAG and NAG, with English reading scores as the nuisance covariate ($p < 0.001$, GRF corrected). The results showed that the NAG exhibited significantly stronger functional connectivity between the left STG and right precentral gyrus (PCG) than the PAG. For the opposite comparison, we did not observe any difference in functional connectivity between the two groups (Figure 2).

3.2.3. FLA-related topological properties

To explore FLA-related topological properties, we applied graph theoretical analysis to test whether topological properties during the English semantic task can distinguish the PAG from the NAG. The results showed significant group differences in network integration and segregation at the sparsity-integrated level. Specifically, the network engaged by the positive group exhibited significantly higher global efficiency (for $0.05 < T < 0.15$ and $0.4 < T < 0.5$) but lower characteristic path length (for $0.05 < T < 0.2$ and $0.4 < T < 0.5$) and clustering coefficiency (for $0.5 < T < 0.5$) than that engaged by the negative group. For the network local efficiencies and small-worldness, we failed to find any difference between the two groups (see Figure 3 for a summary of these findings).

3.2.4. Brain-behavior relationships

To reveal the brain-behavior relationship, we applied mediation analysis to examine whether the relationships between FLA and foreign language performance could be explained by attitude-related brain activity and functional connectivity.

At the activity level, adding activation in the left STG as a mediator showed that left STG activation significantly and indirectly mediated the relationship between FLA and foreign language reading performance (see Figure 4A; indirect effect = −0.60, 95% CI = [−1.18, −0.12], $p < 0.05$).

At the connectivity level, adding FC of the left STG and right PCG as a mediator showed that the association between FLA and reading performance was mediated by FC (see Figure 4B; indirect effect = −0.69, 95% CI = [−1.43, −0.16], $p < 0.05$). Taken together, our findings indicated that the FLA influenced foreign language performance through task-related brain activity and connectivity.

4. Discussion

In the present study, we first used task-based fMRI to investigate the neurobiological correlates of FLA from brain activation, functional connectivity, and large-scale brain network levels and the roles of FLA-related brain activity and connectivity in connecting FLA and foreign language achievement. Overall, our study identified the neural markers of the FLA and the neural paths of the FLA that influence foreign language learning and achievement.

4.1. Brain activity markers differentiating PAG from NAG

At the whole-brain level, we found that NAG showed enhanced activation in the left STG in the English semantic judgment task compared to the PAG.

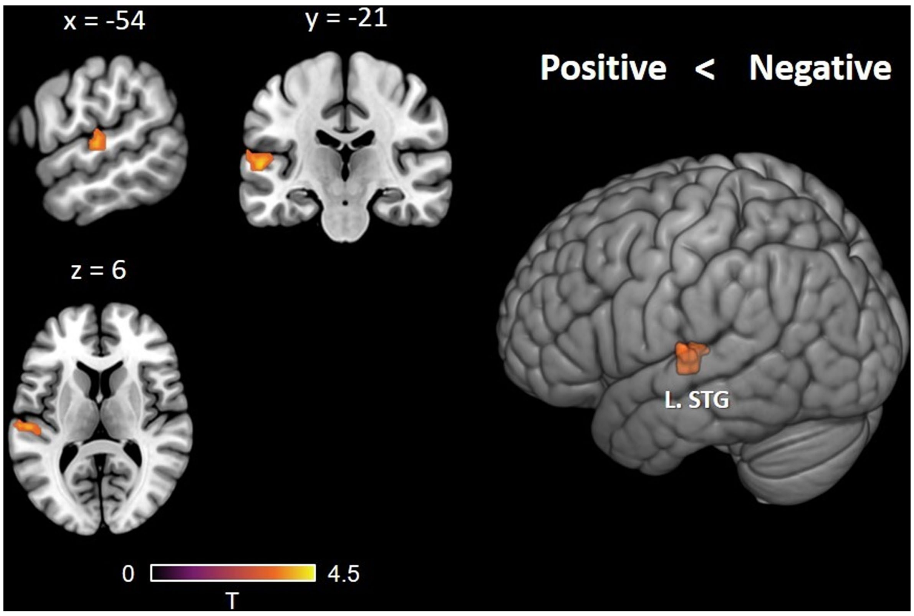

FIGURE 1
Brain activation differences between the PAG and NAG in the English semantic judgment task. After controlling for English reading fluency, increased activation in the left STG was observed when comparing the NAG with the PAG.

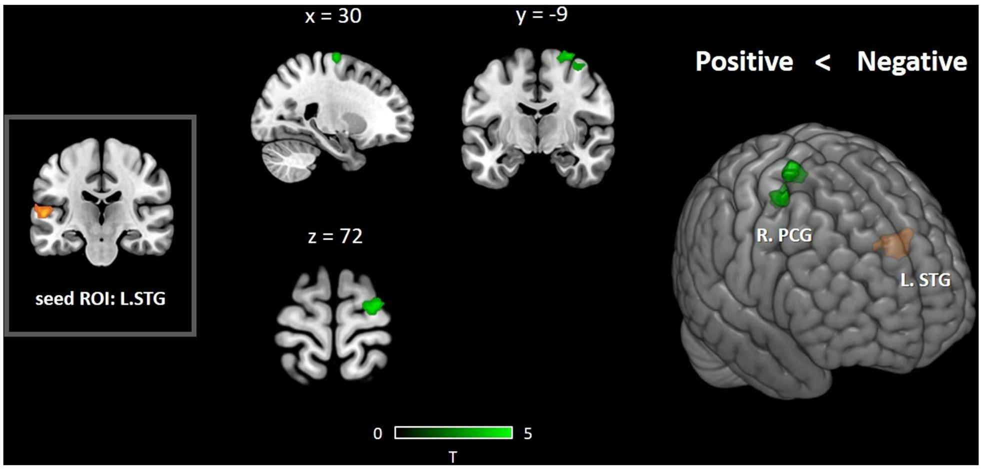

FIGURE 2
Seed-based functional connectivity differences between the PAG and NAG in the English semantic judgment task. After controlling for English reading fluency, increased FC between the left STG and right PCG was observed when comparing the NAG with the PAG.

The left STG is generally considered a core brain region in language function, and it is primarily involved in auditory processing and speech comprehension (Gernsbacher and Kaschak, 2003; Martin, 2003). Importantly, the left STG and adjacent gyral regions have repeatedly been related to audiovisual print–speech integration, especially grapho-phonological conversion (Blau et al., 2009; Kronschnabel et al., 2014; Ye et al., 2017). In addition, previous studies found that this area played important roles in integrating phonological decoding and semantic information to facilitate semantic access in the process of English word reading (Hu et al., 2010). For example, increased left STG activation has been observed when bilingual participants performed English semantic tasks (Tan et al., 2005). In other words, the left STG plays important roles in both audiovisual print–speech integration and phonology-semantics integration. More importantly, as an important region of the core language system, the activation in the left STG was supramodal or modality independent and showed shared cortical activation across spoken, written and signed languages in Dutch speakers, Chinese monolinguals, and Chinese speech-sign bilinguals (Liu et al., 2020).

Generally, brain systems that involve affect, motivation, learning, and memory have been hypothesized to underpin the influence of positive attitudes on academic learning and achievement (Chen et al., 2018). Indeed, Chen et al. (2018) studied math attitudes by employing a single-digit-addition task and found that a positive attitude was associated with increased engagement of the MTL learning-memory system (bilateral hippocampus) but not the affective-motivational system (amygdala or ventral striatum).

In addition to the hippocampal memory system, previous studies on math attitudes also reported that math attitudes correlated with activation in the left IFG when the participants performed a single-digit multiplication task, but this attitude-related IFG activity was observed only for children with positive math attitude but low math skill, and they argued that IFG activity might reflect controlled effort and the retrieval of multiplication facts (Chen et al., 2018; Demir-Lira et al., 2019; Suarez-Pellicioni et al., 2021).

In our dataset, we only observed attitude-related activation in the NAG, and this finding is generally consistent with Demir-Lira's results. In their study, they observed that positive attitudes toward math correlated with less activation in the left IFG. With respect to activity intensity (e.g., increased or decreased), the neural function of academic attitudes seems to be partly domain independent. Since the current study employed different tasks from previous studies (e.g., Chen et al., 2018), it is likely that the different observations are process-driven instead of domain-driven. It is worth mentioning that these two driven might be intermixed and hard to separate from each other. Based on evidence from math attitudes, the larger involvement of the left STG might indicate that negative learners require more effort to recruit phonological processing and semantic integration during English word reading and facilitate task performance.

4.2. Functional connectivity markers differentiating PAG from NAG

In addition to differentiating the PAG from the NAG, the activity of the left STG also differed in terms of functional connectivity (FC). Specifically, the seed-based correlation analysis revealed that the FC between the left STG and right precentral gyrus (PCG) was stronger in the negative group than in the positive group. The left PCG has been well documented to be implicated in many functional MRI studies of language and reading (Dehaene et al., 2001; Yen et al., 2019), and some studies related the right PCG to higher-order cognitive mechanisms, such as language production and comprehension (Dickens et al., 2019). Specifically, the right PCG was activated during phonetic planning and concrete semantic representations (Papeo et al., 2015), and it played an important role in sound-motor integration during word generation (Alario et al., 2006). In addition, the right PCG has been reported to be one of the crucial regions for bilingual language control (Luk et al., 2012), and connectome analysis found that early Japanese-English bilinguals showed dense connectivity between the right putamen and PCG compared to Japanese monolinguals and late bilinguals (Mitsuhashi et al., 2020).

Because the left STG is also related to a variety of language processing, the reinforced STG-PCG connectivity in the negative

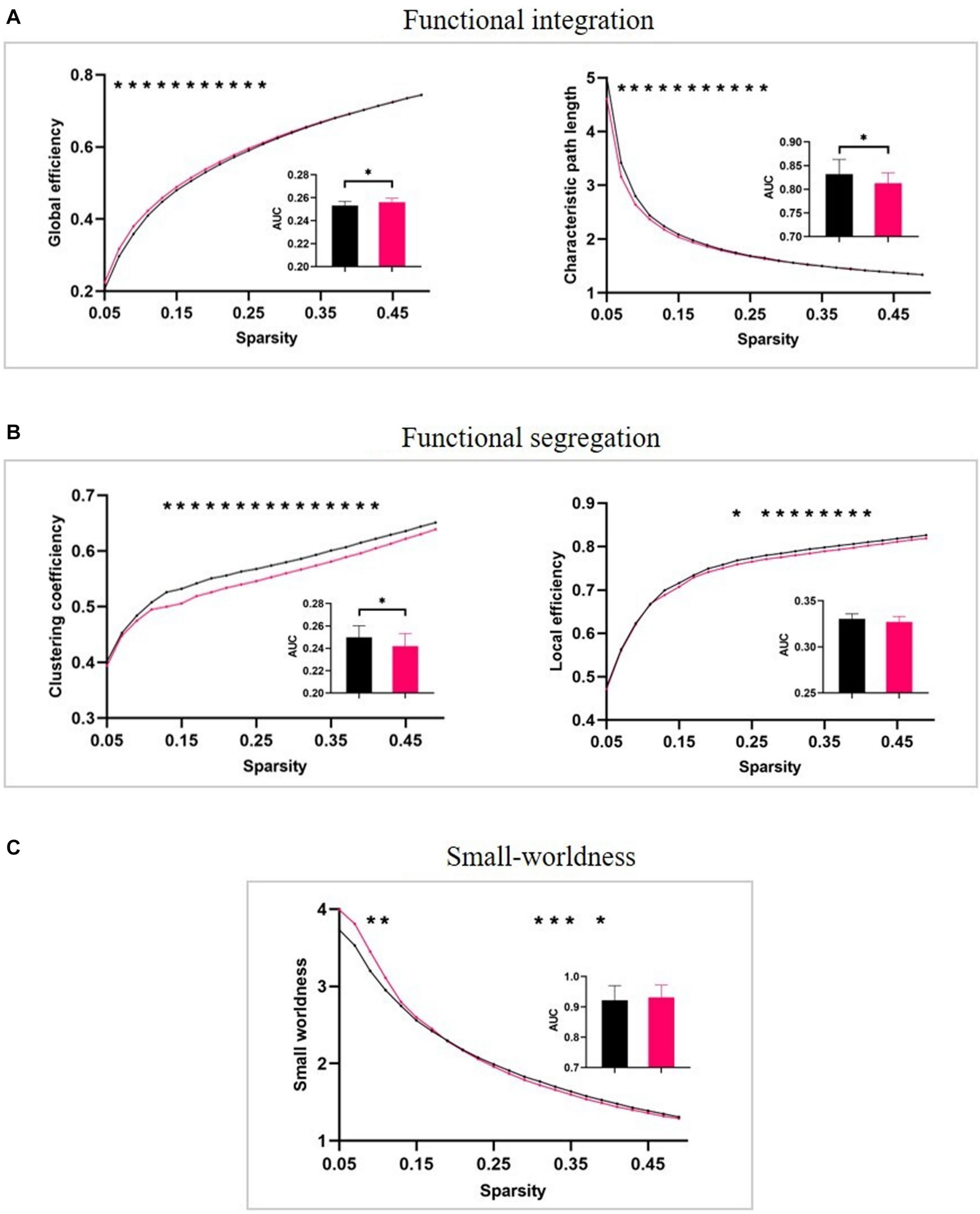

FIGURE 3
Between-group comparisons in graph properties of functional networks. **(A)** functional integration: global efficiency (E_{glob}) and characteristic path length (L_p), **(B)** functional segregation: clustering coefficiency (C_p) and local efficiency (E_{loc}), and **(C)** small-worldness. Inset maps (with mean and standard error) show significant group effects of the area under the curve (AUC) in E_{glob}, L_p, and C_p, $p < 0.05$.

learners may reflect increased investment in reading-related cognitive resources. Furthermore, the negative learners exhibited reinforced FC between the left and right hemispheres to improve their performance during semantic decision-making. Indeed, a previous study supported this possibility and showed that interhemispheric functional brain connectivity could predict new language learning success in adults (Sander et al., 2022). In short, although the role(s) of the right PCG in foreign language attitudes remains unclear, we speculate that the FC between the left STG and right PCG plays a critical role in maintaining reading performance, especially for negative learners.

4.3. The topological properties of the large-size brain network differentiating PAG from NAG

To reveal brain network properties that differentiate the PAG from the NAG, we compared the network topology between the positive and negative learners using graph theory analysis.

The results showed that the positive group displayed significantly higher global efficiency (Eg) and shorter characteristic path length (Lp) in the whole-brain network than the negative group, suggesting that positive learners have more efficient and

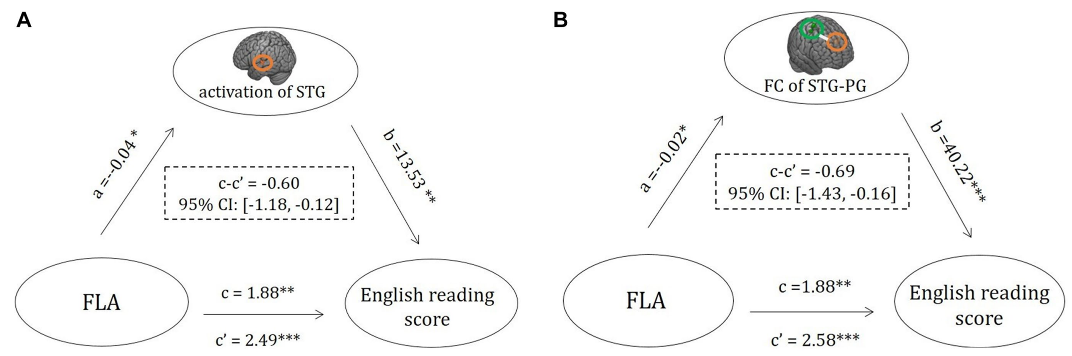

FIGURE 4
The potential pathways of FLA-related neural markers that mediate FLA and foreign language performance. **(A)** Pathways of left STG activity that mediate FLA and foreign language performance (reading fluency) and **(B)** pathways of FC of STG-PCG that mediate FLA and foreign language performance (reading fluency). FC, functional connectivity; PCG, precentral gyrus. *$p < 0.05$, **$p < 0.01$, ***$p < 0.001$.

extensive neural pathways to bring them an advantage in network integration capability (Achard and Bullmore, 2007; Rubinov and Sporns, 2010). In contrast to the PAG, the NAG showed an increased clustering coefficient (Cp), which indicates a greater tendency for functional segregation and the formation of clustered connections (Bullmore and Sporns, 2012).

Although the relevance between network topology properties and academic attitudes has not yet been established, evidence from other domains showed that a brain network with intensifying integration and weakening segregation was associated with cognitive advantages. For example, compared with L2 reading, L1 reading recruited a more globally efficient but less clustered functional network topology, which represents more optimized functional network organization during L1 processing (Feng et al., 2015), and individuals with more active moods and less anxiety have larger global efficiency and shorter path length during tasks (Park et al., 2014, 2016). In addition, evidence from short-term language training suggested that less segregation (smaller clustering coefficient) was associated with successful language learning (Sheppard et al., 2012; Yang et al., 2015), and children with L2 reading impairment exhibited higher local network efficiency (Liu et al., 2016). In the context of this study, English semantic judgment is a complex cognitive process that requires the interactive collaboration of several brain networks involved in orthographic, phonological, and semantic processing (Xu et al., 2005; Binder et al., 2009; Friederici et al., 2009; Price, 2012). Therefore, positive learners likely could easily and flexibly use long-range neural pathways to integrate whole-brain resources, and this coherent and cost-efficient network organization could help them more efficiently complete the foreign language task. Notably, we could not infer causal relationships between FLA and brain network properties in the present cross-sectional study. In this sense, future studies should explore this issue based on longitudinal designs.

4.4. The neural pathways connecting FLA with academic performance

Behaviorally, stable associations between FLA and foreign language achievement have been repeatedly reported in previous investigations (Masgoret and Gardner, 2003; Zhang et al., 2020; Papi and Khajavy, 2021). What are the potential neural pathways underlying these associations? To answer this question, we performed brain-behavior mediation analysis. Our results showed the critical roles of left STG activation and STG-PCG functional connectivity in mediating the relationship between FLA and foreign language performance, and these findings provide important insights for understanding the roles of FLA-related brain activation and FC in foreign language processing and learning. Since the left STG and right PCG are important regions for lexical-semantic processing (Tan et al., 2005; Hart et al., 2012), and the left STG plays a hub-like role in successful second language learning (Yang et al., 2015), we speculate that negative attitudes related to STG hyperactivation and intensive STG-PCG connectivity might reflect a higher effort or requirement for lexical-semantic processing in the NAG to compensate for the global inefficiency of the brain network and further promote in-scanner foreign language performance, and the results from mediation analysis supported this possibility. Although negative correlations were identified between FLA and left STG activation and STG-PCG connectivity, positive correlations were revealed between reading performance and brain activation as well as functional connectivity. These findings suggest that although we failed to find attitude-specific activity in the learning-memory system (e.g., hippocampus) or emotion-motivation system (e.g., amygdala or ventral striatum), academic attitudes might exert their effect through task-related brain regions (e.g., STG) or networks (e.g., STP-PCG connectivity). In summary, our study indicated that left STG activity and STG-PCG connectivity might be potential neural pathways that explain the impact of FLA on foreign language achievement. More specifically, the FLA might affect STG activity and functional connectivity and further influence individual academic performance.

It is worth mentioning that the sample size of the present study is relatively small, which may increase the probability of false positive effects (Ioannidis, 2005) and lead to low power (Ioannidis, 2005; Bossier et al., 2020). Future studies with a larger sample size or longitudinal design could deepen our understanding of the mechanism of FLA.

5. Conclusion

In conclusion, the current study demonstrated, for the first time, that subjective academic attitudes have objective neural signatures and can reshape individuals' brain activities in the task state. The FLA is associated with changed activity of the left STG, FC of the STG-PCG, and the topological properties of the brain network during the English reading task. Since the STG and PCG play important roles in language and reading, these findings imply that FLA-related neural signatures might not rely on the learning-memory system or emotion-motivation system but depend on task-related brain regions or networks. Importantly, compared with existing studies of math attitudes, the neural signatures of academic attitudes seem to be domain specific. More importantly, academic attitude-related neural predictors underlie the potential pathways that contribute to individuals' foreign language performance.

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 the Institutional Review Board of Beijing Normal University. The patients/participants provided their written informed consent to participate in this study.

Author contributions

YPW and DL designed the study. DL and XW analyzed the data, drew the figures, and wrote the manuscript. YPW checked and,revised and edited the manuscript. YZW, YC, and DL performed the experiments. All authors contributed to the article and approved the submitted version.

Funding

This study has been supported by the Scientific and Technological Innovation 2030 - the major project of the Brain Science and Brain-Inspired Intelligence Technology (2021ZD0200500).

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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TYPE Hypothesis and Theory
PUBLISHED 01 August 2023
DOI 10.3389/feduc.2023.1215510

Check for updates

OPEN ACCESS

EDITED BY
Lorna Uden,
Staffordshire University, United Kingdom

REVIEWED BY
Stamatios Papadakis,
University of Crete, Greece
Fauziah Sulaiman,
University Malaysia Sabah, Malaysia

*CORRESPONDENCE
Tracey Tokuhama-Espinosa
✉ traceytokuhamaespinosa@fas.harvard.edu

†These authors have contributed equally to this work and share first authorship

RECEIVED 02 May 2023
ACCEPTED 23 June 2023
PUBLISHED 01 August 2023

CITATION
Tokuhama-Espinosa T and Borja C (2023) Radical neuroconstructivism: a framework to combine the *how* and *what* of teaching and learning?
Front. Educ. 8:1215510.
doi: 10.3389/feduc.2023.1215510

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Radical neuroconstructivism: a framework to combine the *how* and *what* of teaching and learning?

Tracey Tokuhama-Espinosa [1,2*†] and Cynthia Borja [2,3†]

[1]Faculty of Arts and Sciences, Harvard University Extension School, Cambridge, MA, United States, [2]Connections: The Learning Sciences Platform, Quito, Ecuador, [3]The Decision Lab, Montreal, QC, Canada

Recent advances in pedagogical research have called attention to the dynamic nature of the teaching and learning process in which the actors mutually influence one another. The understanding of how this works in the brain—the specialized neural networks related to this process—is often limited to neuroscientists but are slowly becoming available to other learning scientists, including teachers. A transdisciplinary approach combining the best information about observable teaching-learning processes from education with newer information from the neurosciences may aid in resolving fundamental questions in the learning process. Teachers' professional formation and development is often structured in segmented topical ways (e.g., pedagogy, evaluation, planning, classroom management, social–emotional learning), to identify important content knowledge (e.g., art, reading, mathematics, STEM), or to appreciate life skills (e.g., collaboration, critical thinking, social–emotional learning). While important, knowledge about the brain, the organ responsible for learning, is typically absent from teacher education. This paper reexamines the evidence from neuroconstructivism and the hierarchy of learning trajectories and combines it with evidence from psychology and the ways humans interact during the teaching-learning process to suggest *radical neuroconstructivism* as a framework within which to organize teachers' professional development. The radical neuroconstructivism framework may contribute to making the content knowledge of teachers' continual professional development more visible.

KEYWORDS

radical neuroconstructivism, mind-brain-education, core notions, learning sciences, learning trajectory, teacher education, holonic thinking, teacher professional development (TPD)

1. Introduction

The quality of education hinges on the quality of teachers (Barber and Mourshed, 2007; Engelbrecht and Ankiewicz, 2016; Boeren, 2019; Organisation for Economic Cooperation and Development, 2020). Teachers' continual professional development (TCPD) covers a wide range of topics (e.g., pedagogy, evaluation, planning, classroom management, social–emotional learning), subject areas (e.g., art, reading, mathematics, STEM), life skills appreciation (e.g., collaboration, critical thinking, social–emotional learning), and should exists throughout one's professional career (Sancar et al., 2021). There are few if any opportunities, however, for teachers to learn how these topics, subject areas, and life skills are supported by neural networks in the brain (Dubinsky et al., 2022), and fewer still about how to improve them (Peters et al., 2020). Understanding the neural underpinnings of knowledge building in the brain—or *neuro*constructivism—may create useable knowledge for teachers.

Placing TCPD within the "messiness" of classrooms (Tokuhama-Espinosa, 2014) and the relevance of cultural contexts (Hammond, 2014) may also contribute to improved learning outcomes as it acknowledges the ways one's learning is influenced by other actors. This dynamic exchange between students-to-students and students-to-teachers and vice versa influences what a learner takes from teaching and, consequently, changes what is learned (Bevilacqua et al., 2019). Recent research shows how individuals co-construct learning experiences (Vieluf and Klieme, 2023), which elevates the role of "others" in individual learning to the extent of deserving the label "radical" (Von Glasersfeld, 1995, 2013). Radical constructivism suggests that an individual's ability to learn is changed by context. To unite neuroconstructivism with the dynamic exchange of learning between actors, we propose a new theory of radical neurocontructivism.

The transdisciplinary field of Mind, Brain, and Education is uniquely positioned to support research into the theory of radical neuroconstructivism as it encompasses micro-level research at the level of neurons, to consideration of individual genetic and epigenetics traits, to the individual in within classroom dynamics, and all the way to macro-level research that consider social and cultural influences on learning (see Figure 1).

Despite the growth of the International Mind, Brain, and Education Society founded in 2007, and the Neuroscience and Education Special Interest Group of the European Association for Research on Learning and Instruction founded in 2010, advancements in designing a curriculum for teachers' professional development around concepts from neuroscience have been few and far between. To explore the potential contributions of radical neuroconstructivism theory to benefit teacher education, the first part of this paper defines and uses *holonic* thinking, a Greek word meaning something that is once a part and a whole. Holonic thinking is a newer conceptual framework to explain the relationships between the many elements in the educational process. This is followed by a brief historical overview of teachers' professional development between the 1980s and today, which shows radical neuroconstructivism as a natural outgrowth of past advances. The second part of the paper offers an example of early childhood education in math and language using studies from neuroscience that are the puzzle pieces of learning trajectories in these two domains. The paper concludes by summarizing how the *how* (pedagogy), *what* (curriculum), and *why* (Mind, Brain, and Education science) of radical neuroconstructivism may improve teacher education (Figure 2).

2. Part 1: Holons

In one of the most famous philosophical psychological undertakings, Arthur Koestler's *The Ghost in the Machine* (Koestler, 1967) observes that all things are both parts and wholes, which he labeled *holons*. "A holon, as Koestler devised the term, is an identifiable part of a system that has a unique identity yet is made up of sub-ordinate parts and in turn is part of a larger whole" (Edwards, 2003, para. 19). Later, Ken Wilber used holons to explain his All Quadrants, All Levels framework (AQAL), which showed the hierarchical nature of each part and whole (Wilber, 2001). This

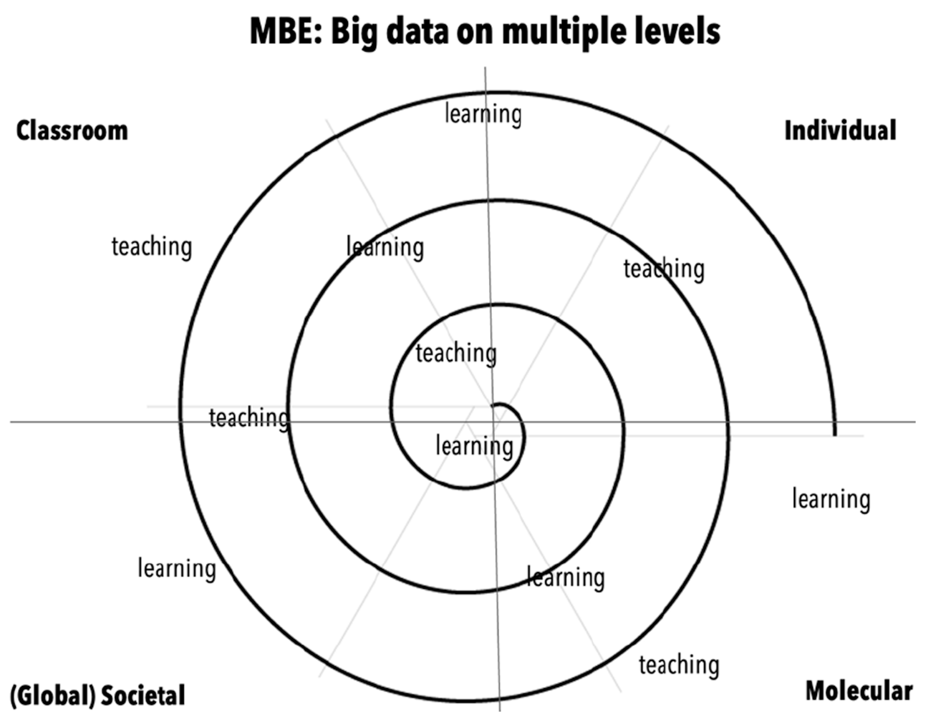

FIGURE 1
Mind, brain, and education research on multiple data collection levels (Tokuhama-Espinosa, 2017).

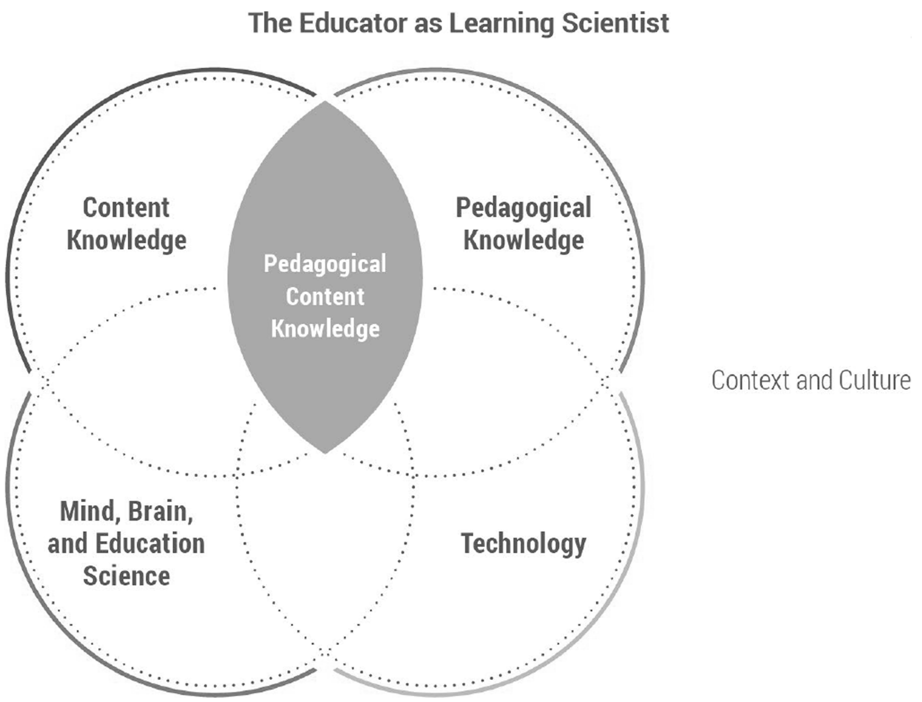

FIGURE 2
The educator as a learning scientist (Tokuhama-Espinosa, 2021a,b). Used with permission of the author.

allowed Gallifa (2019, p. 15) to describe "integral thinking" using a holonic approach to explain the complex nature of all learning through relationships build on hierarchies.

Based on Koestler's definition, everything in the natural world is a holon. A child, for example, is a holon as he is a whole on his own, but he is also a part of a family. A leaf is a holon because it is a whole unto itself, but it can also be a part of a tree. A person's brain is a holon as it is a whole entity on its own, but also part of the person's body. Holonic thinking embraces the idea that not only can everything be a part of something bigger, but each holon can be broken down into smaller parts as well. The child is made up of body parts, which in turn are made of flesh, blood, bones, and muscles (that can themselves also be broken down into ever smaller parts). The leaf can also be broken down into fibers and chemicals, which in turn can also be broken down further. A person's brain can also be broken down into different types of cells, proteins, and so on. In short, everything is a holon, a whole on its own and a part of bigger things that can also be broken down into smaller elements.

2.1. Holonic thinking and teachers professional development

Holonic thinking offers a new lens through which to view challenges in teaching and learning. Education is a holon. It can be considered a part of the Learning Sciences, as well as an academic field on its own, and can be broken down into smaller elements. Teacher education is also a holon. It is part of Education, but can also be broken down into elements, such as *how* to teach [pedagogy and didactics (methodology, activities and strategies)] and *what* to teach (content, curriculum, learning how to learn). The ability to evaluate and give good feedback; how to use technology appropriately; what is needed to create inclusive classrooms; how to differentiate; the cultivation of social–emotional skills to nurture oneself and others, among other elements, are all holons and sub-elements of teachers' continual education. Both pedagogy and curriculum are parts and wholes, as are all of the other topics and skills that contribute to good teaching and successful learning.

Merging the *how* (e.g., pedagogy) with the *what* (e.g., curriculum) of the teaching-learning dynamic yields teachers' pedagogical content knowledge (TPCK) (Gess-Newsome, 2013). In contrast to general best practice teaching, TPCK displays a more nuanced understanding of the interventions that are most appropriate given a specific subject matter and age group. For example, the specialized knowledge teachers must have to anticipate the errors and knowledge of how to correct them differs when teaching math to 3rd graders versus teaching English to high school students. Shulman's (1987) seminal work in this field elevated the mechanistic approach of teaching from a simple delivery system of facts to include a more subtle and precise knowledge base required of teachers both of their subject matter and for the correct pedagogical interventions that can be used to reach educational objectives.

Technology was added to TPCK around 2004 and yielded what many now call the TPACK (Technology, Pedagogy, and Content Knowledge) Model (Mishra and Koehler, 2006). Technology, and specifically educational technology tools, both aid traditional learning as in the correction of objective assessments (e.g., multiple-choice question quizzes), for instance, as well as force society to rethink the role of traditional educational design. *If the only goal of schooling is to gain knowledge and knowledge can be learned using mobile devices, then why go to school at all?,* one might ask. Such reflections help elevate the expectations of schooling and also change the expectations of what teachers' roles are within those schools. For example, the existence of technology that provides content knowledge in a subject area like math reduces the expectation that teachers use time in class reciting math facts (knowledge) (Donahoe et al., 2019) and elevates expectations that they now use their time applying the use of that information (skills), or how to cultivate values around the information, such as learning how to think like a mathematician (attitudes) (Seufert et al., 2021). Some argue that the role of school was never about transmitting factual knowledge, but rather to nurturing of the whole child (Perkins, 2009) by considering his context, likes and dislikes, and particular learning needs (Moon et al., 2020), and that technology can give teachers more time to personalize the teaching-learning experience (Schmid et al., 2022).

Technology has also introduced Artificial Intelligence and machine learning into educational processes (e.g., ChatGPT) which has forced teachers to pivot in ways that will likely change the teaching-learning dynamic forever. Whereas in the past students were judged by their ability to produce *answers* on standardized tests (Cunningham, 2018), large language models like ChatGPT will force students to come up with better *questions* relevant to their unique contexts (Lund et al., 2023). Technology can serve to make some types of learning more personalized and tailored to individual needs, enhancing learning outcomes. To learn to leverage these new technologies and to participate in their design, teachers will necessarily also need to learn more about the ways that both artificial intelligence and real human intelligence work. This new need has catalyzed a renewed interest in the learning sciences, specifically Mind, Brain, and Education (MBE) science.

In viewing the teacher as a learning scientist one can combine pedagogy, content, technology and MBE to suggest a new approach to teacher formation (Tokuhama-Espinosa, 2021a,b). Mind, Brain, and Education science adds a *why* to the *how* and *what* of teaching as it explains the reasoning behind certain teaching interventions (pedagogy: *how*) and content (curriculum: *what*).

As the newest addition to teachers' basic skills, Mind, Brain, and Education science and the International Mind, Brain, and Education Society (IMBES) were founded in 2007 to help practitioners understand how the brain learns in order to verify the best teaching methods to reach the most students (Tokuhama-Espinosa, 2010). MBE has proven implications for pedagogical interventions (Tokuhama-Espinosa, 2014, 2021a,b; Wilson and Conyers, 2020) as well as has made inroads in curriculum (Larrison, 2013). According to Dubinsky et al. (2022, p. 267), "the foundational contributions from neuroscience regarding how learning occurs in the brain reside within one of Shulman's seven components of teacher knowledge (Shulman, 1987, p. 8), Knowledge of Students… teachers must also (and increasingly) know what happens inside students' brains." It has been suggested that "knowledge of learners and their characteristics" (Shulman, 1987, p. 8) should now include clarity about how the brain understands concepts in domain-specific areas (e.g., Hawes and Ansari, 2020), leverages emotions for better cognition (e.g., Li et al., 2020), and co-constructs meaning making in group situations (Immordino-Yang et al., 2019).

Holonic thinking can be used to reframe the way we view teacher education and our understanding about the teaching and learning process. Both philosophers (e.g., Procter, 2011) and neuroscientists (e.g., Lamme, 2006) believe learning is based on fundamental building blocks of knowledge, which permit the construction of increasingly complex thinking (Hernández Armenta et al., 2019). Thinking is a holon that is part of the learning process itself, and it can be broken down into smaller and smaller parts. Disaggregating this thinking process into its smaller parts allows for a more precise understanding of all of the elements that contribute to how people learn both in classroom settings and in the world more broadly. To construct new learning, people build on previous knowledge using the foundation of what have been called core notions (Bada, 2015). Some of the building blocks of learning are explained in neuroscientific studies, but few teachers benefit from this information in their initial teacher training or in continual professional development (Deans for Impact, 2015). Furthermore, the majority of the contributions from neuroscience to education are related to pedagogy, not curriculum. In a review of all the articles from the *Mind, Brain, and Education* journal 2007–2018, just 24 of 312, less than 1%, related to curriculum (Nouri et al., 2022, pp. 58–59). This confirms Dubinsky and colleagues' belief that "Neuroscience professional development provides neuroscience principles that teachers can learn and apply to distinguish among pedagogical choices, plan lessons, guide in-the-moment classroom decisions, and inform the views of students. Neuroscience does not directly invent new pedagogies. Rather, knowledge of neuroscience guides teachers in choosing appropriate pedagogies, pragmatically informing teaching" (Dubinsky et al., 2022, p. 267).

One potential way to extend MBE into Education both pedagogically and through curriculum is through *radical neuroconstructivism*. Radical neuroconstructivism is an as-of-yet untested theoretical framework for understanding the teaching-learning dynamic. It is difficult to prove as it rests against the backdrop of a student's prior experiences and contexts which vary greatly. It also depends, however, on universal building blocks, meaning some generalizations relating to all humans can be posited.

3. Radical neuroconstructivism

Constructivism has been used successfully as a framework to explain the way the mind orders the hierarchy of learning concepts, beginning with an approach from developmental psychology and spilling into education (Piaget, 1923). To construct new learning, people build on previous knowledge using the foundation of these core notions (Solis-Stovall, 2020). The individual does not live in the world alone, however, so many researchers, especially those in social learning theory (e.g., Bandura, 1977), raise the importance of constructivism within environments and social contexts. When the environment and the role of others is also incorporated into the constructivist learning model, this is called *radical constructivism* (Von Glasersfeld, 1995, 2013). Ernst Von Glaserfeld used the constructivist ideas suggested by Vico (1710), Ceccato (1964/1966), and Piaget (1968) to which he added on the cyclical, iterative processes that occurs as people try "to order the as such amorphous flow of experience by establishing repeatable experiences and relatively reliable relations between them," (Von Glasersfeld, 1984, p. 5). Von Glaserfeld's ideas were firmly grounded in strong philosophical roots but they carried over naturally into the teaching and learning environment as the means by which societies devise formal education. Von Glasersfeld (1984, p. 20) uses "radical" to emphasize the relationship of a person to reality and explains that rather than a "picture-like (iconic) correspondence or match, radical constructivism sees it as an adaptation in the functional sense." This means that the very contact with others or with new information would change a person's understanding of it. An idea in one's head about how to approach a problem, a work of art, or a piece of literature, is changed by the simple act of articulating it out loud for another person. While words facilitate thinking, they are not the same thing as thinking. One's understanding of one's own ideas require no explanation to one's self; once put "out in the world" one must modify the choice of words to meet others' levels of understanding. Furthermore, teachers must modify this language use to meet a variety of learners' needs in the same setting. This means that what is thought cannot always be articulated clearly to others, resulting in the voice in our heads being different than the one we hear as we speak (LaValley, 2022).

A second aspect of the "radical" nature of thinking and learning relates to the individual themselves in time. As all new learning passes through the filter of prior experience (Tokuhama-Espinosa, 2008), and the older we get the more experiences we have, our interpretation of the world becomes more colored by what we already know. For example, reading *The Diary of Anne Frank* at age 13 is different at age 18 or 30 or 50, not because the book is different, but *you* and your context are different.

Radical constructivism emphasizes the role that others can play in influencing how an individual thinks about information. A person may have one kind of idea in their mind, but when they articulate this in words to another person, the idea changes Hitchcock, (2018). And by listening to the response of the other to the idea, the idea is again changed. This dynamic process of idea transformation is what turns constructivism within the individual into a social exchange in the world (De Soto, 2022). Teachers know that classroom exchanges between students and with themselves modify the way they think about information.

After radical constructivism, a newer concept from neuroscience, *neuroconstructivism*, took hold. *Neuroconstructivism*, like its predecessor *constructivism,* requires that lower or base level concepts be learned before more complex ideas can be built upon them and that this occurs in a neurophysiological way structuring primary networks before secondary ones can be scaffolded upon them. Dekker and Karmiloff-Smith (2011) were some of the first to suggest that the combination of behavioral studies, neuroimaging, and genetics research in both typical and atypical populations pointed to the existence of neuroconstructivism. By Karmiloff-Smith et al. (2018) were able to formulate a new theory of human development based on neuroconstructivism.

"Neuroconstructivism" is a term used to explain the physical scaffolding of core notions and conceptual knowledge (Broadbent and Mareschal, 2019) "that influence the emergence of mental representations in postnatal development," (Westermann et al., 2007, p. 75). The brain makes basic neural connections, then successively more complex ones based on experiences which are unique to the individual (Mareschal et al., 2007; Westermann et al., 2007, 2011; Karmiloff-Smith et al., 2018). As Westermann and colleagues pointed out in their seminal article *Neuroconstructivism* (Westermann et al., 2007, p. 75), "Cognitive development is explained as emerging from the experience-dependent development of neural structures supporting mental representations." The scaffolding of conceptual understanding permits the construction of neural networks that eventually become the learning manifested in observable behavior, such as the ability to read a story or to do a math problem. Earlier studies in neuroconstructivism showed that when certain fundamental networks were missing, a child was unable to perform certain tasks and future tasks that relied on that initial task. For example, a child can scaffold a new understanding of subtraction upon the basis of addition. If the child knows how to add well, then learning to subtract takes relatively few steps to master. However, many children have gaps in core notions in mathematics and because they have missing conceptual knowledge in addition, they are unable to easily learn subtraction. This is not only true for math but for every other subject taught in school or experienced in the real world.

In 2019, Tokuhama-Espinosa suggested that this promising new idea could be merged with Von Glaserfeld's thinking and coined the term *radical neuroconstructivism.* Building off both the dynamic, iterative exchange of an individual with his or her surroundings, and the constant co-construction of neural networks of the brain's design and on a natural hierarchy of conceptual knowledge, this paper suggests that radical neuroconstructivism can potentially create the framework to explain how people learn.

3.1. Meaning making

This paper suggests that the *radical* aspect of radical *neuro*constructivism involves "meaning making," made popular thanks to Neil Postman and Charles Weingartner's chapter in *Teaching as a Subversive Activity* (Postman and Weingartner, 1969). In their work they point out that "meaning making also forces us to focus on the individuality and the uniqueness of the meaning *maker*," (Postman and Weingartner, 1969, p. 91). This was a shift from prior teaching and learning models in which school subjects (math, language, art, history, and so on) were meant to be learned by all individuals in the same way without much consideration for the variability among students. Postman and Weingatner valued that the way people understand their world and make meaning depends to a great extent on what they already know and how they have already habituated responses to certain contexts and stimuli. When one begins with the meaning *makers* (students) in mind, and the many differences they each have, it becomes clear why the learning processes in school do not always go to plan; the individuality of the learner changes the outcomes.

To make meaning of one's world, an individual first perceives the environment through the senses, as Aristotle suggested 2,500 years ago (Caston, 2020). This sense perception is perceived and interpreted in the brain by comparing what is known from prior experiences to the incoming information from the outside world (Tokuhama-Espinosa, 2008). The prior experiences a person can have are grounded in both formal and informal learning, as well as based on life experience. Life experiences and a person's environment also includes one's culture, which like all social environments, influences learning (Gay, 2018). People then construct meaning by taking the new information that is being perceived in the brain and comparing it with what they already know from prior experiences including their cultures and contexts. Contexts and cultures include contact with other people in settings like schools and with teachers and students.

Complementary to Postman and Weingartner (1969) work is a newer interpretation of *meaning making* from Mary Helen Immordino-Yang's lab. She suggests knowing how others feel (empathy) and think (mentalizing), then comparing that to one's own thinking and feeling, helps derive meaning (Immordino-Yang and

Knecht, 2020). That is, seeing how others react in situations and comparing that to how one would act themselves in the same situation helps people make meaning out of the world: "Radical neuroconstructivism changes based on the student-teacher and student–student dynamics, and other human exchanges converging with what the student already knew about the information mediated by the pedagogical choices of the instructor," (Nouri et al., 2022, p. 115). The interaction with the outside world, compared with internal knowledge and memories, is modified by other students and by the teacher, making it "radical" as compared to static (Nouri et al., 2022). Radical neuroconstructivism explains why different students react differently to teaching strategies and activities. The unique reaction of each student to what the teacher and other students do in the classroom changes the way the student thinks about the information, and ultimately how he or she learns.

Students come to class with their past experiences, their cultures, and their genetic profiles which then interacts with exchanges they have with other students, with their teacher, and the teacher's choice of pedagogies. The intricate interaction between this large number of complex variables results in learning. As shared in *Crossing Mind, Brain, and Education Boundaries* we contend:

> Rather than a simple "Teach A-Learn A" scenario, MBE (Mind, Brain, and Education) teachers appreciate that learning is complex, and influenced by multiple factors. MBE practitioners understand that:
>
> (a) students come to class on an uneven playing field due to genetic inheritance;
> (b) students do not share the same prior experiences;
> (c) what the student already knows influences how they learn;
> (d) knowledge, skills, and attitudes influence learning;
> (e) the student's relationship with the other learners influences learning;
> (f) the student's relationship with the teacher influences learning;
> (g) the teacher's execution of the methodology, strategy, or activity influences learning;
> (h) the learner's self-perception in the class context/environment influences learning;
> (i) what else is vying for the student's attention can influence learning.
>
> These different actors, actions, reactions, and interactions can all influence learning outcomes (Nouri et al., 2022, pp. 115–116).

Taken as a whole, radical constructivism suggests that the individual's conceptual knowledge of the world is shaped by what he or she already knows, and how, when, why, and by and with whom the stimuli occurs.

4. Core notions as basic building blocks of cognition

The concept of core notions has been posited in philosophy (e.g., Schaffer et al., 2009), demonstrated in cognitive psychology (e.g., Tuominen and Kallio, 2020), and imaged in neuroscience (e.g., Skerry and Saxe, 2016). Core notions are pre-requisite knowledge at each stage of the learning process. Furthermore, each progressive level of knowledge has its own core notions and depends on those that proceed them (Sporns, 2022); counting has different core notions than calculus, for example, *and* calculus depends on counting. Similarly, higher order language depends on the lower notions that sustain them; the core notions within word choice are different from higher order language notions such as metaphorical thinking, for example. Metaphorical thinking, in turn, depends on word choice (Black, 1962). In the best-case scenario, the curriculum or order of subjects a child learns, should first introduce fundamental core notions and once mastered, advance to subsequently more complex notions.

Countries around the world use the evaluation of math and language as proxies for intelligence (Tokuhama-Espinosa, 2019) often in combination with more complex tools that depend on them, such as reasoning (Flanagan and McDonough, 2018). Both math and language are comprised of "core notions" or fundamental building blocks of knowledge, which permit the construction of learning and progressively more complex thinking (Hernández Armenta et al., 2019; Solis-Stovall, 2020). Examples of "core notions" include any fundamental or pre-requisite knowledge needed to complete a higher order task and are characterized by *thinking* states rather than *process* memorization. For example, zero ("0") is a complex notion, which, if misunderstood, can lead to problems with understanding "ones" and "tens" and eventually decimals, negative integers, and other key notions in mathematics (Hansen et al., 2020). In a second example, the core notion of a mental number line can be used to see addition or subtraction problems inside one's head (Dehaene, 2003; Haman and Lipowska, 2021). Problems like "1 + 2 = 3" are visualized in the mind's eye and such visualization is vital to developing efficient, accurate and speedy arithmetic skills (Sari and Olkun, 2020). An understanding of zero combined with a mental number line permits a visualization and understanding of negative numbers, and eventually the addition and subtraction of both positive and negative integers (Vest and Alibali, 2021). If zero or the mental number line are not learned by children, they will be unsuccessful in early math, and consequently higher math. Missing core notions in children are a primary reason kids "hate math" (Liu, 2016); the inability of teachers to identify these gaps is exacerbated by the fact that teachers themselves often have missing core notions (Ball, 2017). Missing core notions in teacher knowledge are also responsible for poor math and language learning by their students (Loch et al., 2015), signifying a systemic problem.

Unfortunately, many students advance through the education system with progressively complex missing core notions (Rist, 2017) for which teachers are unprepared. Bartelet et al. (2014, p. 657) noted that learning difficulties in math can spring from at least six different origins: "(a) a weak mental number line group, (b) weak ANS (Approximate Number System) group, (c) spatial difficulties group, (d) access deficit group, (e) no numerical cognitive deficit group and (f) a garden-variety group," suggesting that a more nuanced look at both gaps in mathematical instruction as well as diagnosis of mathematical sub-types of errors is necessary to help students achieve. If teachers do not know about core notions or their hierarchy in brains, they cannot easily identify the types of errors being committed by students. This is an example of what Dubinsky and colleagues meant by improving teacher Knowledge of Students "and what happens inside their brains," (Dubinsky et al., 2022, p. 267).

Research into language has also identified many core notions which can go unattended in early childhood education. One area that has received a lot of attention is vocabulary. Educational research has demonstrated for years that rich, age-appropriate vocabulary lays the foundation for complex thinking (Hirsh-Pasek and Golinkoff, 2003) and that poor vocabulary is correlated with academic failure (Baker, 1995). Hart and Risley (2003) "*The Early Catastrophe*," showed a "30 million word gap by the age of 3" for children from lower social economic status homes due to less exposure to rich conversational exchanges, fewer books in the home, and parental knowledge of language development (Johnson et al., 2017). Researchers warn that "denying the existence of the 30-million-word gap" suffered by underserved children "has serious consequences" (Golinkoff et al., 2019, p. 985). Therefore, explicit vocabulary instruction is a part of several early childhood training programs, but not all. Despite neuroscientific evidence showing that "children's conversational exposure is associated with language related brain function," (Romeo et al., 2018, p. 700) that do not exist without human conversation, other researchers have pointed out that "talk alone will not close the 30-million word gap" (Wasik and Hindman, 2015, p. 50) and that meaningful interactions with language use in varied contexts are necessary to fill in the gap. Appropriate word use in the right context with increasingly complex patterns is fundamental to language development but not all early childhood education programs emphasize this and not all teachers know vocabulary is a fundamental building block in learning.

Other core notions in language development relate to normal speech patterns, including the grammar and syntax that is acceptable in local cultural contexts. While all humans learn to speak from an innate language sense (Chomsky, 2000; Pinker, 2009), the parameters of acceptable speech differs by country (e.g., British to American), region (e.g., Hawaii to Texas), district (e.g., English in the Bronx versus English in upper Manhattan), and even neighborhood (e.g., East Los Angeles versus West). Furthermore, the way humans speak differs greatly from how they write, especially from informal to academic contexts (Chafe, 1985). This puts children whose core notions of grammar and syntax that differ from standard English in school at an academic disadvantage from the start (Au, 2009). When the school's standard English differs greatly from the home language, students first need to learn the "foreign" language of school before they can be successful in other subjects. This sets up many for failure. Many find learning the school language a burden and decide they are not "cut out for school," and/or "hate reading," (Hale and Crowe, 2001), and too many drop out (Rumberger and Lim, 2008) for this reason. This paper proposes that teaching core notions in language in a more orderly trajectory may change students' negative attitudes toward education as the neuroconstruction of core notions in an orderly way may ease the path by creating a more solid early learning foundation.

In this paper it is suggested that a deeper and better understanding of the radical neuroconstructivist building blocks of cognition may permit a more precise and orderly introduction of skills that would be coherent with the brain's natural progression from lower-to-higher-level knowledge. This would improve the design of the curriculum, allowing more children to succeed.

5. Teaching and learning: practical applications of radical neuroconstructivism

While psychology has contributed to educational best practice for over 100 years (Berliner and Calfee, 2014), contributions from neuroscience have only recently been regularly incorporated into teacher professional development (Deans for Impact, 2015). Thanks to neuroscientific insights, there have been improvements in pedagogy, didactics, strategies, activities, and methodologies for learning at all levels of education (K-16). This is especially true of new knowledge about the dynamic exchange between cognition and affect (e.g., Immordino-Yang, 2015), meaning making (e.g., Zittoun and Brinkmann, 2012) at the crossroads of culture and cognition (Rawlings and Childress, 2021), and the importance of student-teacher relationships (e.g., Hattie and Zierer, 2017).

While *how* to teach has benefitted greatly from neuroscientific insights, *what* to teach has received less attention; the promise of neuroscientific insights into shaping the design of curriculum, such as in early literacy or math learning, is an underexplored area for educators. A key impediment to the use of neuroscientific knowledge in education is that the puzzle as a whole has not been constructed using all of the parts that are available.

6. Part II: learning trajectories and radical neuroconstructivism

The second part of this paper uses the examples of early years language and math to explain the holonic thinking from Neuroscience, Psychology and Education that can lead to a better neuroconstructivist curriculum design for schools. Education and Psychology have helped construct a relatively orderly curriculum (Tokuhama-Espinosa, 2019), which takes into consideration human variability (e.g., Mezirow, 2018). It is possible that additional evidence from Neuroscience can bring a more nuanced understanding of typical gaps in notions that children may experience. We propose that the ability to diagnose missing core notions earlier will allow more timely and accurate interventions in early childhood education.

Learning depends on the quantity, quality, and timing of exposure to learning objectives (Paolini, 2015). The literature suggests the earlier an academic competency is introduced to a learner, and the stronger its subsequent constructivist development, the more likely a positive learning outcome in that competency (Bakken et al., 2017) due to the quantity and quality of exposure. The literature also suggests that quality experiences at pre-school benefits both kids who had enriching home experiences and those who did not (Fuson et al., 2015). Klein and Starkey's research showed that a broad socioeconomic gap in informational mathematical knowledge was present at the beginning of the *pre-kindergarten* year. This gap included not just numerical concepts and arithmetic reasoning, but also spatial concepts and geometric reasoning, knowledge of patterns, and nonstandard measurement (Klein and Starkey, 2004). One theory for this occurrence relates to the kinds of play experienced by different socio-economic groups (Missall et al., 2015). This means some kids arrive at school with missing core notions as compared with their peers due to the contexts in which they were raised. Quantity, quality, and timing are aided by exposure to core notions in a *logical order* which strengthens neural pathways for future learning (Karmiloff-Smith, 2009; Galván, 2010). Nowhere is this more evident than in research on early language development and early math.

The stimulation of language development (i.e., vocabulary, correct word order, social cues for interaction, and so on) begins in the home with the family and is generally developed further in regular school settings by trained educational professionals. Similarly, pre-numeracy skills (*ordinality* as parents count a child's fingers and toes out loud; *magnitude* as he is given "more" or "less" of an object; *symbolic numeric representation* as he blows out the candles on a birthday cake, and so on) aid in the development of a child's *number sense* (Dehaene, 2011) and are cultivated in a similar pattern (Campbell, 2014) through adult-child interaction. High-quality early childhood education can play an important role in the effective development of early academic skills development (Campbell et al., 2012) but requires a home (parent)-school (teacher) partnership with a shared plan (Missall et al., 2015). We suggest that by disaggregating math and language into sub-skills in a neuroconstructivist trajectory for mastery, we may potentially improve the diagnosis of problems and aid in the selection of more accurate remediating activities with the goal of ensuring all children have a successful start to school.

It is only since the turn of the century that neuroimaging studies have offered definitive proof of the changes in the brain during infant learning. This includes cognitive development such as typical growth rate, myelination, top-down modulation, and changes in cortical hubs, (Deoni et al., 2011; Fransson et al., 2011; Holland et al., 2014; Dempsey et al., 2015; Emberson et al., 2015). While teachers and parents generally understand that infants learn at an astounding rate, few are aware that infants have a preverbal early number sense that permits them to estimate quantities, gauge relative size and judge spatial orientation (Dehaene, 2011). One way to make these ideas clearer to parents and teachers is by showing neuroconstructivist studies alongside more familiar learning trajectories shared by pediatricians (Morris et al., 2020). To do this, it is important to update basic professional knowledge in the learning sciences for both math and language.

6.1. Four categories of networks found in the literature

Understanding the neural networks of learning requires holonic thinking in which the smallest of parts are placed in context with their larger wholes. Between 2013 and 2023 we reviewed over 1,000 studies on early math and literacy and sought to create a taxonomy of early learning using their content. Initially, research was limited to domain-specific studies that looked at language and mathematical networks in the brain in young children. Domain-specific networks overlap significantly between language and math (Caravolas et al., 2012), and include pathways for symbols, patterns, order, relationships, and categories (Tokuhama-Espinosa, 2019). It soon became apparent, however, that while learning to read or do math involves domain-specific areas, learning also depends heavily on the general cognitive abilities of memory, attention, and executive functions (specifically inhibitory control, cognitive flexibility, and working memory), and in fact, without well-functioning general cognition, it was all but impossible to have domain specific instruction.

In addition to domain-specific networks and general cognitive networks, the literature also identified numerous studies related to the context in which a person learns. A learner's relationships with others in the class and with the teacher influence learning (Frey et al., 2019), as does the student's self-esteem and belief in him or herself to learn (Agir, 2019). Motivation is also part and parcel of the learner context (Ahn et al., 2019), and one's awareness of the impact their social contexts, including culture, has an important influence on one's ability to learn in a given classroom setting (Osher et al., 2020). The literature clearly shows the uneven playing fields upon which different children begin their lives. The risk and protective factors of family (parents' education, SES, marital status), homes (homelessness, proximity to parks and libraries, daycare options), as well as the impact of culture and social contagion on well-being influence learning.

Finally, there were also several studies concerned with the physiological sensory networks related to the senses, specifically hearing, vision, and touch. Well-functioning sensory systems influence learning. While there were fewer studies about the role of gustatory and taste influence on learning, a student's ability to see, hear, and learn through touch or haptic knowledge (Connolly, 2019) was vital to every learning encounter. Vision and hearing tests are standard procedure in many early childhood education programs, but not in all (Oosthuizen et al., 2023). This suggests 16 neural networks divided into four categories explained below (Figure 3).

The four categories have a total of 16 distinct neural networks within them, and those networks sub-divide into numerous pathways, which we define as *core notions* in domain areas such as math (Table 1) and language (Table 2). For the purposes of this paper, the neural pathways are considered "distinct" if one or more brain areas is different. For example, auditory working memory and visual working memory differ in the sensory input but not in memory areas and are treated as distinct networks (Figure 3).

6.2. Domain specific networks

The concept of "learning trajectories" (Gorard, 2006) is based on research into "hierarchies of skills" (Kuhn et al., 2000) and the general concept of constructivism proposed in the mid-1900s in which basic concepts are established before higher-order thinking occurs (Piaget, 1967). We generally presume that the curriculum structure of a country, state, or district should order the information we consider valuable to teach into the right trajectory so that students can logically advance from one concept to another. Curriculum structures around the world are surprisingly similar in terms of subject area content. The same subjects are taught all around the world at roughly the same time (Tokuhama-Espinosa, 2019), which allows for international comparative studies like TIMMS (Trends in International Mathematics and Science Study) and PIRLS (Progress in International Reading Literacy Study). Independent of country values, social economic status, culture, public-private-parochial status, political inclination, age group, and rural–urban status, all school systems, large and small, teach math and language. Language and mathematics are cornerstones of all educational programs worldwide (Pinar, 2013), and are vital to both an individual's success as well as country competitiveness (Organisation for Economic Cooperation and Development, 2021). Among countries that conduct national exams, these are the only two universally tested subject areas due to the foundations they lay for other academic fields (Martin and Mullis, 2013), including history, art, the natural, social, computer, and hard sciences. Despite their importance, even within-country studies show there is no consensus on the best ways to teach core subjects such as math and language.

6.2.1. Neuroconstructivist mathematics

Constructivism can explain why some learning goals are not met. As mentioned earlier, a child cannot learn subtraction (*learning goal*) if he does not understand addition (*pre-requisite knowledge*). To

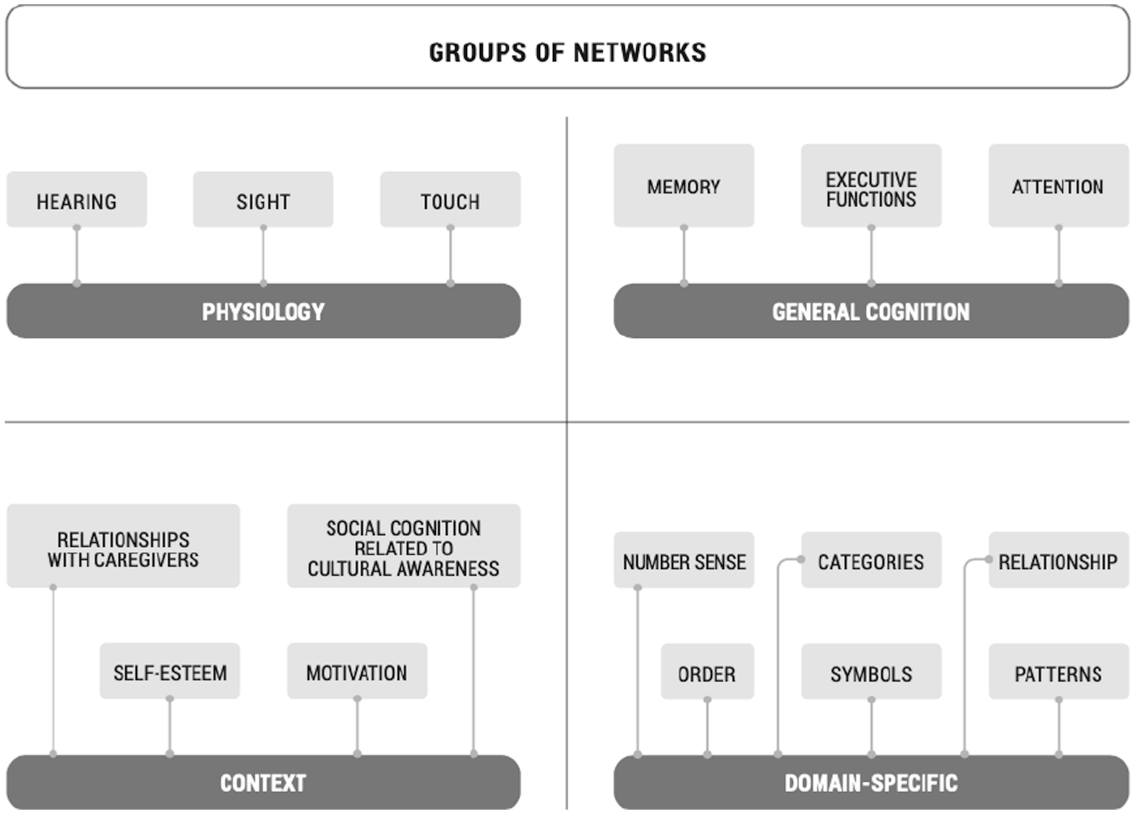

FIGURE 3
Four categories of networks found in the literature.

be successful in basic arithmetic, he will first need to understand everything underpinning the concept of addition, and then make his way to the higher-order skill of subtraction, which involves dozens of core notions. If any one of the pre-requisite skills laid out in the hierarchy is not developed properly, the child will not be unable to master the new knowledge upon which it is based (Vergnaud, 1982). It is important to acknowledge that some children will learn to mechanically identify the pattern of subtraction questions and appear to dominate that skill, but in reality, they will simply be using extended working memory and knowledge of patterns to feign knowledge (Ball, 2017). True understanding means the learner can comprehend, identify, explain, use, and *transfer knowledge* as evidenced by creating their own problems correctly (Ringel and Springer, 1980).

Math, like all subject area, has four categories of networks were sub-divided by 16 neural networks. In math, we have further divided the networks into smaller parts—core notions—or neural pathways. In our review of the literature on the neural correlates of math, we have identified over 130 distinct pathways (Table 1), which can be observed in over 180 behaviors related to mathematical development. For example, the observable, visible behavior of counting can be observed in a classroom as the student counts on his fingers, counts objects, sings a song about counting, labels number symbols on a number line, among dozens of other activities. The invisible neural pathways involved in counting include decoding, discrimination and enumeration; distance and congruity; finger counting; inhibitory control and visual processing; number versus non-number symbols, among others (Table 1). In both math and language there are more observable behaviors than invisible networks, suggesting that the same networks sub-serve more than one behavior.

The main ways neuroscience can contribute to educational practices is by (a) assuring all neural pathways are stimulated through a variety of activities so that (b) all sub-skills and prerequisite knowledge are learned. This can be done if (c) core notions are approached in an orderly, hierarchical way. Additional benefits include the ability to (d) identify missing core notions early, therefore (e) making teaching interventions more precise, which would prevent children from school failure.

Table 1 is not exhaustive, and offers just a sampling of possible core notions, some of which have additional sub-elements.

Other evidence shows how the brain learns to code mathematical symbols and to distinguish between "3," "three," and "***" in a *triple code* (Dehaene, 1992; Dehaene and Cohen, 1995; Dehaene et al., 2003; Schmithorst and Brown, 2004; Klein et al., 2014), and estimate *magnitude* (i.e., Lourenco and Longo, 2011; Notebaert et al., 2011; Linsen et al., 2015; Lyons and Ansari, 2015). The brain also rotates shapes (i.e., Harris and Miniussi, 2003; Frick et al., 2013; Thompson et al., 2013; Bruce and Hawes, 2015), and understands the role and meaning of *place value* (i.e., Butterworth et al., 2011; Ferguson, 2015; Lambert and Moeller, 2019).

Yet other research clarifies the neural networks related to the role of fixed *sequence* (Grafton et al., 1995; Orban et al., 2011; Kidd et al., 2012; Pariyadath et al., 2012), and how the brain determines a general sense of *numerosity* (i.e., Piazza et al., 2004, 2006; Xu et al., 2005;

TABLE 1 Examples of differences in the math literature between educational curriculum and neuroconstructivist design.

Early mathematics	
Educational curriculum (Observable, visible behavior)	**Neuroconstructivist design (Invisible neural pathways that must be stimulated to produce visible behavior)**
Counting	• Decoding (e.g., Cho et al., 2011) • Discrimination and enumeration (e.g., Nan et al., 2006) • Distance and congruity (e.g., Kaufmann et al., 2005) • Finger counting (e.g., Soylu et al., 2018) • Inhibitory control and visual processing (e.g., Fan et al., 2014) • Number vs. non-number symbols (e.g., Zhang et al., 2012) • Numerosity (e.g., Zago et al., 2010; Hannula-Sormunen, 2015) • Sequential sensory and motor event (e.g., Kansaku et al., 2006) • Visual enumeration (e.g., Demeyere et al., 2012) • Numerical and non-numerical ordinality (Kaufmann et al., 2009; Lyons and Beilock, 2013)
Comparing and ordering	• Categories and concepts (e.g., Miller et al., 2003) • Format comparison (e.g., Olkun et al., 2015) • Number words vs. digits (e.g., Hung et al., 2015) • Number-size inference (e.g., Kaufmann et al., 2006) • Numerical analogical reasoning (e.g., Wu et al., 2016) • Numerical magnitude and working memory (e.g., Knops, 2006) • Numerical ordering and symbolic arithmetic (e.g., Knops and Willmes, 2014) • Ordinal representation (e.g., Attout et al., 2014) • Relational reasoning and symbolic distance (e.g., Hinton et al., 2010) • Semantic and perceptual processing of number symbols (e.g., Holloway et al., 2013) • Spontaneous focus on numerosity (e.g., Hannula-Sormunen et al., 2016) • Symbolic number comparison (e.g., Ansari et al., 2005; Mussolin et al., 2010; Goffin and Ansari, 2016)
Recognizing numbers and "subitizing"	• Difference between subitizing and counting (e.g., Yue-jia et al., 2004; Vuokko et al., 2013) • Difference between subitizing and estimation (e.g., Burr et al., 2010; Cutini et al., 2014) • Gestalt perception in visual quantification (e.g., Bloechle et al., 2018) • Multiple object individuation (e.g., Mazza and Caramazza, 2015) • Pre-attentive and serial processing (e.g., Piazza et al., 2003) • Tactile consciousness (e.g., Gallace and Spence, 2008)
Coding and codification	• Symbolic vs. non-symbolic number identification (e.g., De Smedt and Gilmore, 2011; Skagenholt et al., 2018) • Math, Letter and Other symbols (e.g., Cantlon et al., 2011; Grotheer et al., 2016) • Analogical thinking (e.g., Vendetti et al., 2015; Marchand and Barner, 2018; Park, 2020) • Abstract to symbolic to concrete (e.g., Donovan and Fyfe, 2019)
Composing numbers	• Approximate quantification categories (e.g., Gandini et al., 2008) • Number processing (e.g., Knops, 2017) • Quantifiers, numbers and numerosity (cardinality) (e.g., Wei et al., 2014; Goffin, 2019) • Roman vs. Arabic numbers (e.g., Masataka et al., 2007) • Triple code (e.g., Skagenholt et al., 2018)
Forms, shapes	• Part vs. Whole comprehension (e.g., Hallowell et al., 2015; Zambrzycka et al., 2017) • Shape descriptions (e.g., Dillon, 2017) • Shape identification (e.g., Scherf et al., 2009; Chen et al., 2021) • Shape reproduction (e.g., Williams et al., 2014) • Preliminary alignment (e.g., Ons and Wagemans, 2012; Fragaszy et al., 2015) • Shape mapping (e.g., Du et al., 2018)
Adding and subtracting	• Abacus mental calculation (e.g., Chen et al., 2006) • Adult vs. child arithmetic processing (e.g., Peters, 2016) • Arithmetic and language (e.g., Baldo and Dronkers, 2007) • Calculation (e.g., Davis et al., 2009) • Manual calculation (e.g., Masataka et al., 2006) • Mental arithmetic (e.g., Artemenko et al., 2018) • Mental calculation (e.g., Gruber, 2001) • Number sense (e.g., Dehaene et al., 2004) • Simple calculation (e.g., Zago et al., 2001) • Symbolic and non-symbolic arithmetic (e.g., Venkatraman et al., 2005)

(Continued)

TABLE 1 (Continued)

Early mathematics	
Educational curriculum (Observable, visible behavior)	Neuroconstructivist design (Invisible neural pathways that must be stimulated to produce visible behavior)
Multiplying and dividing	• Component processes of inductive reasoning (e.g., Jia et al., 2011) • Developmental dissociation (e.g., Prado et al., 2014) • Error detection (e.g., Kroeger, 2012) • Fractionating and working memory (e.g., Metcalfe et al., 2013) • Mental calculation (e.g., Gruber, 2001; Hanakawa et al., 2003) • Naming actions versus naming spatial relations (e.g., Damasio et al., 2001) • Problem solving (e.g., Lin et al., 2015) • Problem-size effect (e.g., Prado et al., 2013) • Working memory (e.g., Metcalfe et al., 2013)
Measuring	• Number-size interference (e.g., Kaufmann et al., 2006) • Numeral classifiers (e.g., Cui et al., 2013) • Numerical distance effect (e.g., Mussolin et al., 2013) • Perceptual similarity (e.g., Axelrod et al., 2017) • Quantity processing of quantifiers, numbers, and numerosity (e.g., Wei et al., 2014) • Repetition and regularity (e.g., Dehaene et al., 2015) • Attributes (e.g., Vingerhoets, 2008; Clements et al., 2022) • Comparisons (e.g., Kaufmann et al., 2006)
Naming geometric shapes	• Description (e.g., Dillon, 2017) • Identification (e.g., Benischek, 2018) • Features of (e.g., Biederman, 2013) • Meaning making (e.g., Voss et al., 2010) • Naming and spatial relations (e.g., Damasio et al., 2001) • Object-based attention (e.g., Ongchoco and Scholl, 2019) • Shape-form shading (e.g., Hou et al., 2006) • Unfamiliar shapes (e.g., Voss and Paller, 2010) • Visual perception (e.g., Pollen, 1999) • Visual context (e.g., Ejima et al., 2007) • Visual search (e.g., Fockert et al., 2004)
Ordinal(ity)	• Fixed order (e.g., Rubinsten et al., 2013) • Unique (e.g., Lyons et al., 2016) • Relative (e.g., Attout et al., 2014) • Counting out loud (e.g., Gordon and Ramani, 2021) • Rank (including before and after) (e.g., Nieder, 2005) • Inverse (e.g., Berch et al., 2016) • Sequence (e.g., Hedenius et al., 2013; Steinemann et al., 2016) • Place value (e.g., Varma et al., 2008; Möller, 2010; Kraut and Pixner, 2023)
Comparing geometric shapes	• Eye tracking (e.g., Verdine et al., 2017) • Haptic to visual (e.g., McLaughlin, 2000) • Letter matching (e.g., Fecteau and Enns, 2005) • Name and shape matching (e.g., Monaghan and Pollmann, 2003) • Multi-sensory processing (e.g., Hulme et al., 1987) • Muscle movement and tracing (e.g., Portnoy et al., 2015) • Small and to-scale figures (e.g., Snapp-Childs et al., 2018) • Spatial rotation (e.g., Knouse, 2006) • Tracing and copying (e.g., Bernbaum et al., 1974) • Visual processing in haptic representation (e.g., Kalenine et al., 2011)
Composing geometric shapes	• Manual imitation (e.g., Braadbaart et al., 2012) • Motor control (e.g., Palmis et al., 2017) • Motor expertise (e.g., Calmels, 2020) • Object categorization (e.g., Athanasopoulos and Casaponsa, 2020) • Object vs. spatial imagery (e.g., Kozhevnikov and Blazhenkova, 2013) • Spatial rotation (e.g., Judd and Klingberg, 2021) • Tactile memory (e.g., Gallace and Spence, 2009)

(Continued)

TABLE 1 (Continued)

Early mathematics	
Educational curriculum (Observable, visible behavior)	**Neuroconstructivist design (Invisible neural pathways that must be stimulated to produce visible behavior)**
Classifications	• Characteristics (e.g., Augustine et al., 2015) • Sets (e.g., Li et al., 2021a,b)
Spatial sense and motion	• Child vs. adult (e.g., Kucian et al., 2007) • Manual training (e.g., Wiedenbauer and Jansen-Osmann, 2008) • Motor development (e.g., Jansen and Heil, 2010) • Sex difference (e.g., Hahn et al., 2010) • Experience (e.g., Hertanti et al., 2019) • Working memory to visuomotor learning (e.g., Anguera et al., 2010) • Two- and three-dimensional shapes (e.g., Neubauer et al., 2010)
Patterning and early algebra	• Alphanumeric equations (e.g., Lee et al., 2007) • Core number systems (e.g., Abreu-Mendoza et al., 2020) • Gesture-based instruction (e.g., Wakefield et al., 2019) • Insight and ordinary problem solving (e.g., Lin et al., 2021) • Math symbols and numbers (e.g., Zhang et al., 2012) • Mathematical mindsets (e.g., Daly et al., 2019) • Pattern analysis (e.g., Johnson et al., 2009) • Relationship of words to math (e.g., Bates et al., 1992) • Strategies (e.g., Rosenberg-Lee et al., 2009) • Rhythmic patterns (Bergeson and Trehub, 2006) • Patterns in music (Geist et al., 2012)
Classifying and analyzing data	• Concept processing (e.g., Ghio, 2013) • Error detection (e.g., Kroeger, 2012) • Object recognition (e.g., DiCarlo et al., 2012) • Syntactic classification (e.g., Forkstam et al., 2006)
Equivalencies	• Spatial-numerical (e.g., Hubbard et al., 2009) • Matching (e.g., Emerson and Cantlon, 2012) • Reproduction (copying) (e.g., Gerván, 2012) • Decomposition (equivalencies) (e.g., Rosenberg-Lee et al., 2015; Xu and LeFevre, 2016) • Division (e.g., Ellis, 2015; Meng and Moriguchi, 2021) • Fractions (e.g., Wortha et al., 2020)
Approximations or estimations	• Calculation (e.g., Gunderson and Hildebrand, 2021) • Spatial orientation (e.g., Sutton et al., 2010; Cheng et al., 2013) • Spatial rotation (e.g., Newcombe et al., 2013) • Length, weight and quantity (e.g., Siegler and Booth, 2004)

Domahs et al., 2010; Anobile et al., 2013). These overlap but are distinct from neural networks related to *approximations*, *estimations* (Gilmore et al., 2014; Kibbe and Feigenson, 2015), and *equivalencies* (Mix, 1999; Hunt, 2011; Price et al., 2013; Chesney et al., 2014). There is also extensive work describing the brain and how it comprehends *arithmetic*, including division (i.e., LeFevre and Morris, 1999; Fehr et al., 2007; Grabner et al., 2009; Ischebeck et al., 2009; Andres et al., 2011; Rosenberg-Lee et al., 2011; Venneri and Semenza, 2011; Bugden et al., 2012), and grasps *proportions* (i.e., Sophian, 2000; Jacob et al., 2012).

Teachers can turn this list of neural pathways for math into useable knowledge in three ways. First and foremost, teachers can embrace the complexity of the brain and the sheer number of pathways involved in learning and resisting simplistic formulas for teaching and learning. Second, teachers can learn how observable behavior maps onto different types of neural networks which will help them better diagnose learning problems or gaps in student knowledge. And third, by understanding that different neural pathways are stimulated by different classroom and life experiences, they can select more efficient and effective learning interventions.

6.2.2. Neuroconstructivist language

Learning trajectories in language are similar to those found in math. In language, the four categories of networks were sub-divided by 16 neural networks that sub-divided into over 90 neural pathways. When matched with the educational literature, there were over 171 observable behaviors related to early language development.

To devise elements for the educational curriculum (left column in Table 2) studies from public policy, pediatrics, and literacy were combined. These studies span from the role of parents in pre-literacy development as correlated with social-economic status (Fernald et al., 2013), racial disparity (Hoff, 2013), current practices in nursery schools around the

TABLE 2 Examples of differences in the language literature between educational curriculum and neuroconstructivist design.

Language and pre-literacy	
Educational curriculum (Observable, visible behavior)	**Neuroconstructivist design (Invisible neural pathways that must be stimulated to produce visible behavior)**
Receptive language	• Action observation (e.g., Marshall et al., 2011) • Auditory discrimination (e.g., Zhao et al., 2021) • Follows multiple-step instructions (good working memory) (e.g., Schneider et al., 2005; Yang et al., 2014) • Joint attention and understanding (e.g., Woodward, 2005; Saby et al., 2012) • Points to appropriate object on command (e.g., Melinder et al., 2015) • Responds to one word commands (“no”) (e.g., Mestres Missé, 2007) • Speech perception and comprehension (e.g., Friederici and Männel, 2013) • Understands role of pointing (e.g., Gredebäck et al., 2010) • Semantic and syntactic sentence processing (Schneider and Maguire, 2019) • Speech discrimination and later grammar (Zhao et al., 2021) • Syntax (Klein et al., 2022)
Productive language	• Speech imitation (spontaneous) (e.g., Garnier et al., 2013; Kokkinaki and Vitalaki, 2013; Szczepek Reed, 2020) • Adjective generation (e.g., Zhang and Pylkkänen, 2018) • Affective contributions to lexical decisions (e.g., Sylvester et al., 2021) • First and second language speech (e.g., Petitto et al., 2012; Cristia et al., 2014) • From auditory to speech perception (e.g., Dehaene-Lambertz et al., 2005) • High frequency sounds, novel sounds (e.g., Gervain et al., 2016) • Human action sounds vs. other sounds (e.g., Geangu et al., 2015) • Intelligible speech (e.g., Khandaker, 2015; Friederici et al., 2017). • Morphology and syntax (e.g., Benavides-Varela and Gervain, 2017) • Noun generation (e.g., Schipke et al., 2012; Takashima et al., 2019) • Plurals and semantic numbers (e.g., Dunagan et al., 2022) • Sentence construction (e.g., Schneider and Maguire, 2019) • Syntactic processing (e.g., Oberecker et al., 2005) • Two-word sentences; three-word sentences (e.g., Werker and Vouloumanos, 2001) • Phonological processing (Powers et al., 2016) • Words and syntax (Takashima et al., 2020)
Vocabulary	• Meaning to object (point to correct picture) (e.g., Takashima et al., 2019) • Movement/gesture and vocabulary (e.g., Skoning et al., 2017) • Object-to-meaning (semantic memory) (e.g., Ferreira et al., 2015; Peeters et al., 2017) • Phonotactic processing (e.g., Steber and Rossi, 2020) • Social cues (e.g., Yu and Ballard, 2007) • Verbs vs. action verbs (e.g., den Ouden et al., 2009; Zhang et al., 2018) • Visual literacy and picture naming (e.g., Deetsch et al., 2018) • Word classification (e.g., Saccuman et al., 2006) • Gesture and semantic memory (de Marco et al., 2022)
Storytelling	• Alliteration (e.g., Pedott et al., 2017) • Audio vs. Illustrated vs. Animated (e.g., Hutton et al., 2020) • Beginning-middle-end (working memory) (e.g., Veraksa et al., 2020) • Gestures and visual support (e.g., Schaadt, 2015; Kartalkanat and Göksun, 2020) • Illustrations and visual support (e.g., D’Angiulli et al., 2015) • Intonation, prosody (e.g., Hupp and Jungers, 2013; List, 2019) • Lexical tone perception (e.g., Liang and Du, 2018) • Pitch and meaning (e.g., Morrill et al., 2015) • Prediction (e.g., Misyak et al., 2010; Lehne et al., 2015; Veraksa et al., 2019; Hasegawa et al., 2021) • Questioning (e.g., Frank et al., 2012; Schipke et al., 2012; Schouwenaars et al., 2018) • Rhythming (e.g., Wagensveld et al., 2013; Hurschler, 2015)
Alphabet	• Audiotactile processing (blind) (e.g., Pishnamazi et al., 2016) • Letters, symbols and digits (e.g., Carreiras et al., 2015) • Symbol vs. non-symbol recognition (e.g., Yamada et al., 2011) • Symbol-to-phoneme recognition (e.g., Katzir et al., 2005; Widmann et al., 2007)

(Continued)

TABLE 2 (Continued)

Language and pre-literacy	
Educational curriculum (Observable, visible behavior)	Neuroconstructivist design (Invisible neural pathways that must be stimulated to produce visible behavior)
Story generation	• Natural skill (e.g., Bers and Cassell, 2000) • Thought to text (e.g., Fayol et al., 2012) • Voice-to-text (e.g., Whitney et al., 2009; Fudickar, 2018; Siok and Luke, 2020; Romanovska et al., 2021)
Spelling	• Isolated impairment (e.g., Gebauer et al., 2012) • Lexicality (e.g., Weiss and Booth, 2017) • Misspelling (e.g., Purcell et al., 2011a) • Phonemic awareness (e.g., Katzir et al., 2005; Booth et al., 2007; Kemény et al., 2018) • Priming (e.g., Cao et al., 2010)
Morphology	• Prefixes and suffixes (Gao et al., 2023) • Morphological processing (Louleli et al., 2022)
Reading	• Fluid reading (e.g., Christodoulou, 2010) • Phonological processing (e.g., Orechwa, 2009; Cherodath et al., 2017) • Syllables to sentences (e.g., Friederici, 2005) • Concrete vs. abstract words (D'Angiulli et al., 2015) • Silently vs. aloud (Xia et al., 2018) • Universal reading network (Feng et al., 2020) • Audio-visual integration (Li et al., 2023) • Functional reading network (Benischek et al., 2020)
Sight words	• Rapid naming (e.g., Misra et al., 2004; Saletta, 2019) • Phonological and semantic processing (Mathur et al., 2020)
Sentence construction	• Sentence reading (e.g., Simos et al., 2011) • Transcription vs. writing (e.g., Wallis et al., 2017) • Syntax and semantic overlap (Fish, 2020)
Text	• Capital vs. small letters (e.g., Dehaene and Cohen, 2010; Augustine et al., 2015; Jung et al., 2015) • Fonts (e.g., Vinci-Booher and James, 2020; Fabiani et al., 2023) • Handwriting vs. print text (e.g., Longcamp et al., 2006; Downey, 2014; Roux et al., 2021) • Mirror reading (e.g., Dehaene et al., 2010) • Print vs. cursive (e.g., Gilet et al., 2011)
Handwriting	• Drawing pictures for meaning (e.g., Gansler et al., 2011; Schlegel et al., 2015; Yuan et al., 2018) • Geometrical shapes to letter formation (e.g., Norton, 2012) • Haptic memory (e.g., Gallace and Spence, 2009) • Motor control (e.g., Simiona, 2016; Palmis et al., 2017) • Tablet versus handwriting (e.g., Lin et al., 2021) • Word shapes and hand gestures (e.g., Nakamura et al., 2012)
Writing	• Symbol systems (Li et al., 2021a,b) • Central and peripheral processing (Purcell et al., 2011b) • Orthographic loop (Richards et al., 2012) • Imagined writing (Baumann et al., 2022) • Global networks of good vs. poor writers (Costa et al., 2022) • Visual-motor networks (Vinci-Booher and James, 2021) • Differences of pencil, keyboard, tablet (Mayer et al., 2020)

world (Halden et al., 2011); and the ways that literacy parallels other milestones in growth (Hoff, 2009). Furthermore, there is documentation of the natural ordering of language skills in children 0–6 (Luinge et al., 2006) described as a natural hierarchy of pre-literacy skills. Literacy understanding from the contributions made by research from second language learners (e.g., Kuhl, 2011) as well as that from language learning delays caused by congenital defects and in cases of autism (McDuffie and Haebig, 2013) have also highlighted the core notions underpinning successful language acquisition. As with Tables 1, 2 right-hand column is comprised of a representative sampling of the various sub-skills or core notions needed to achieve the educational curriculum indicated in the left column.

This sampling of the many pathways found within the networks makes the precision of their activation more targeted than general guidelines found in education. For example, educators often talk about "language problems," whereas a neuroscientist might speak about the precise problem of semantic memory, non-letter symbols used in reading, or the way that prosody influences meaning.

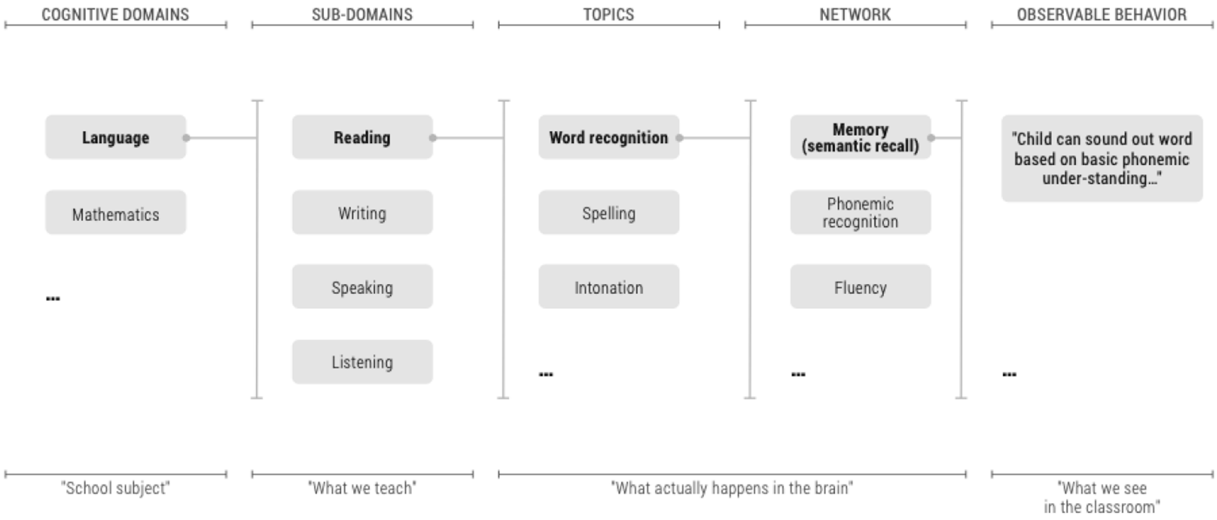

FIGURE 4
From academic domains to the brain and back.

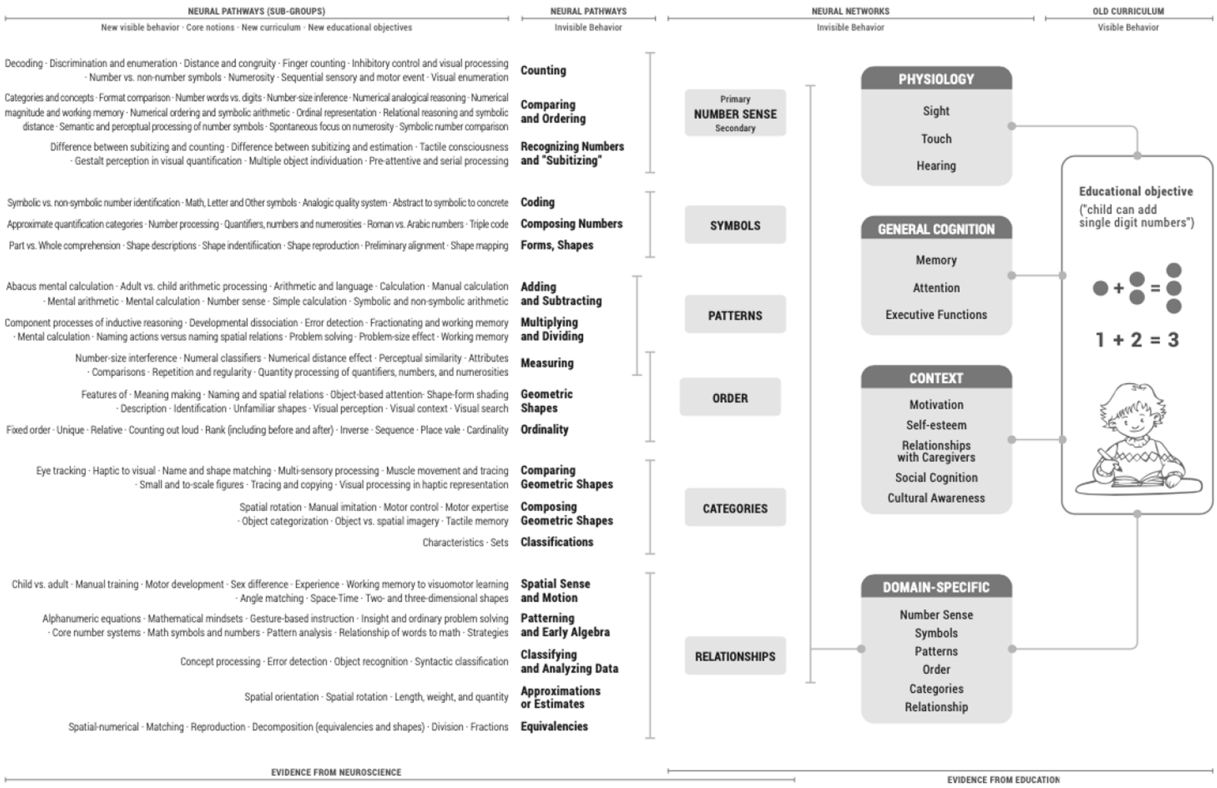

FIGURE 5
From invisible core notions to the visible educational curriculum.

Educators can learn from neuroscientists as the more precise the diagnosis, the better, more accurate the cure. That is, if a teacher know the "language problem" is one of symbol-to-sound (phoneme) difficulties, they will use a different intervention than if the problem is one of semantic retrieval.

The domain-specific areas of math and language were subdivided into (a) innate sense (i.e., innate number sense; innate language sense), (b) symbols, (c) patterns, (d) order and (e) categories, and (f) relationships.

One way to use the terminology from Education and Neuroscience together is in Figure 4.

To display a transdisciplinary understanding of early math and pre-literacy, it is necessary to travel from visible behavior to invisible neural networks, as seen in Figure 5.

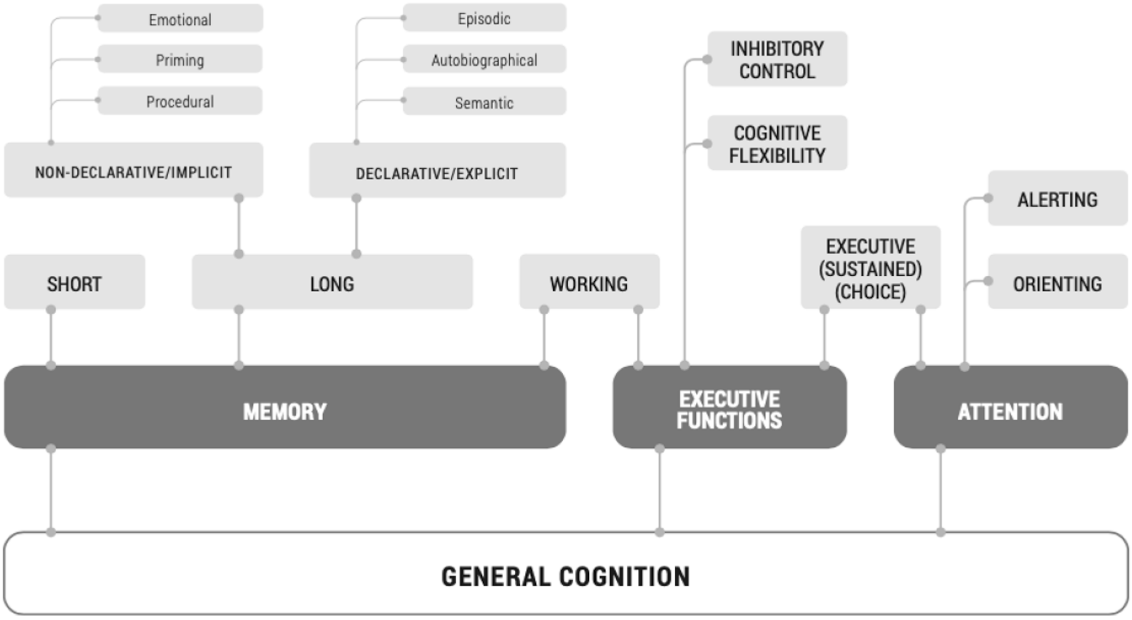

FIGURE 6
Neural pathways within the general cognition networks.

The domain specific neural networks for math and language are important when students encounter problems limited to those subject areas. If the student has both math and language problems, however, it is more likely than not that the student has a general cognitive network problem (Figure 6).

6.3. General cognition networks

All domain specific learning in math and language also depend on general cognition as well. General cognition is founded on two core pillars of learning: well-functioning (a) memory systems and well-functioning (b) attention systems (Tokuhama-Espinosa et al., 2020). Based on evidence from neuroimaging, both memory and attention make up (c) Executive Functions. Memory is sub-divided into complex (1) long-term memory, which in turn is divided into (i) non-declarative and (ii) declarative, (2) working memory, and (3) short-term memory. Executive Functions are sub-divided into (1) working memory, (2) cognitive flexibility, and (3) inhibitory control. Attention is sub-divided into (1) executive or sustained attention, (2) alerting, and (3) orienting systems (Fan and Posner, 2004). Just as each network in the domain specific areas of math and language sub-divide into numerous neural pathways (core notions), so do general cognitive networks. For example, long-term declarative memory networks can be further divided into semantic, autobiographical and episodic memory pathways, and there are likely many more.

6.4. Context networks

It is now commonly accepted that the context within which one learns influences the learning itself (National Academies of Sciences, Engineering, and Medicine, 2018). The literature review revealed studies of learning context related to the role of (a) social contagion in learning, how (b) relationships with caregivers influenced learning, the role of (c) self-esteem in learning, and how (d) motivation impacts learning (Figure 7). These pathways, in turn, were sub-divided even further. For example, social contagion (a) was viewed differently in studies related to (1) cultural awareness and context as compared with (2) theory of mind research.

6.5. Sensory networks

All learning occurs through the senses, as Aristotle pointed out over 2,500 years ago. Without sensory perception no learning is possible, let alone math and language. Hearing, Sight, and Touch studies were included in the review. Smell and taste were less prevalent in both the neuroscientific and educational literature and were therefore not included though future studies should consider their possible roles in learning math and language (Figures 8–10).

There are 10 identifiable pathways that emerge from the Hearing network, including distinct pathways for (a) pitch, (b) tempo, (c) tone, (d) prosody, and (e) loudness. Related to orientation within hearing were two distinct pathways related to echolocation or sounds that come from the (f) left versus right and from (g) foreground versus background sounds. Other pathways relate to the integration of sight and hearing through the interpretation and use of (h) hand gestures to support auditory compression. It was also found that the brain perceives and interprets (i) human voices distinctly from other sounds. Finally, there were multiple studies on (j) auditory processing, which combined sensory, motor, memory, and attention sub-systems.

Within Vision, it was found that there are 11 distinct pathways including those for (a) color, (b) luminance, (c) size, and (d) proximity.

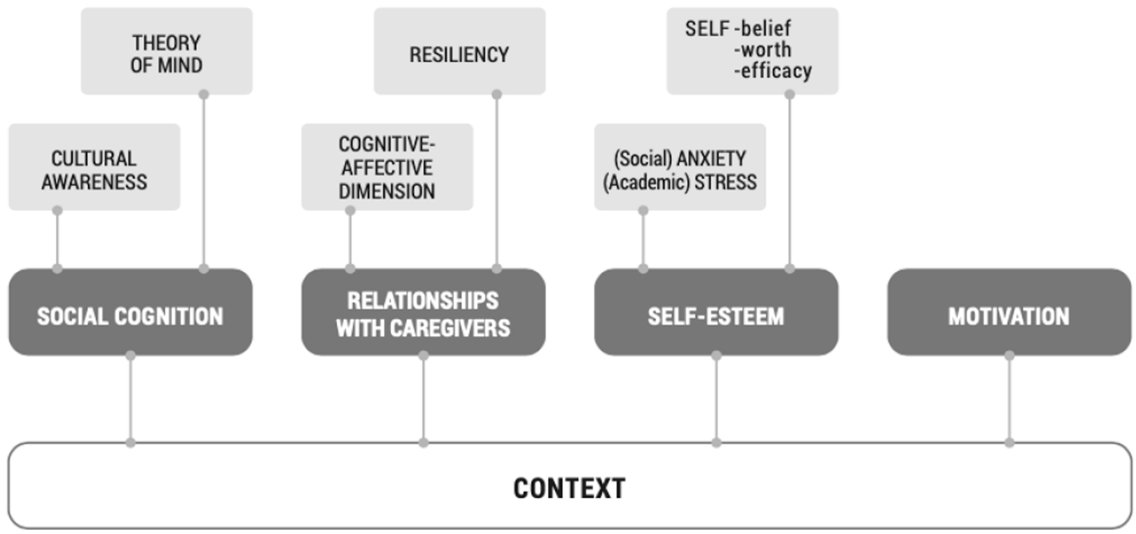

FIGURE 7
Neural pathways within the context network.

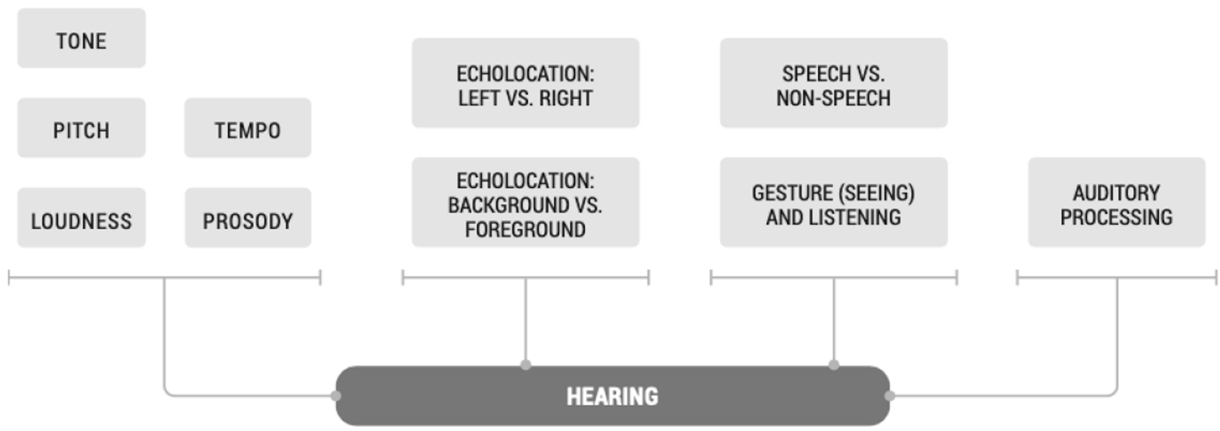

FIGURE 8
Neural pathways within the hearing network.

Visual pathways also distinguish (e) perception vs. action, (f) motion, and (g) spatial–temporal contrast. It was also found that as the most studied human sense, (h) visual crowding, occupies a distinct neural pathway from (i) spatial frequency, which is also distinct from the brain's ability to search and determine (j) saliency in its surroundings. Finally, after 40 years of debate, it appears clear that the brain distinguished (k) human faces from other objects (Burns and Bukach, 2019).

The sense of Touch involves at least seven different neural pathways, but as the least studied of the senses, it is likely that additional research may extend these findings related to haptics and perception. There are distinct neural pathways for (a) visual motor integration, (b) scribbling, (c) fine motor tracing, and the (d) tactile recognition of shapes. Additionally, (e) writing—distinct from scribbling—(f) drawing, and the understanding of the (g) variant expressions of writing (such as capital versus small letters and cursive versus print, as well as different font forms) are also in distinct neural networks.

Of the four types of neural networks (domain specific, general cognitive, context, and sensory), sensory networks have the most research and the longest history. The sensory networks are based on perception from outside stimuli and memories of stimuli. Sensory networks were the gateways into the other three categories of networks. All four network categories are vital for learning to occur and should become part of teachers' knowledge. We suggest that sharing these 16 neural networks in teacher training can potentially improve teacher diagnosis of learning problems by increasing their nuanced understanding of "language problems" or "math problems" and relating them to the core notions of these subjects.

7. Discussion

On the basis of evidence from the learning sciences, we present a novel theory called Radical Neuroconstructivism, which is supported by extensive research from psychology, neuroscience, and education (Von Glasersfeld, 1984, 1995, 2013; Westermann et al., 2007, 2011; Dekker and Karmiloff-Smith, 2011; Hitchcock, 2018; Karmiloff-Smith et al., 2018;

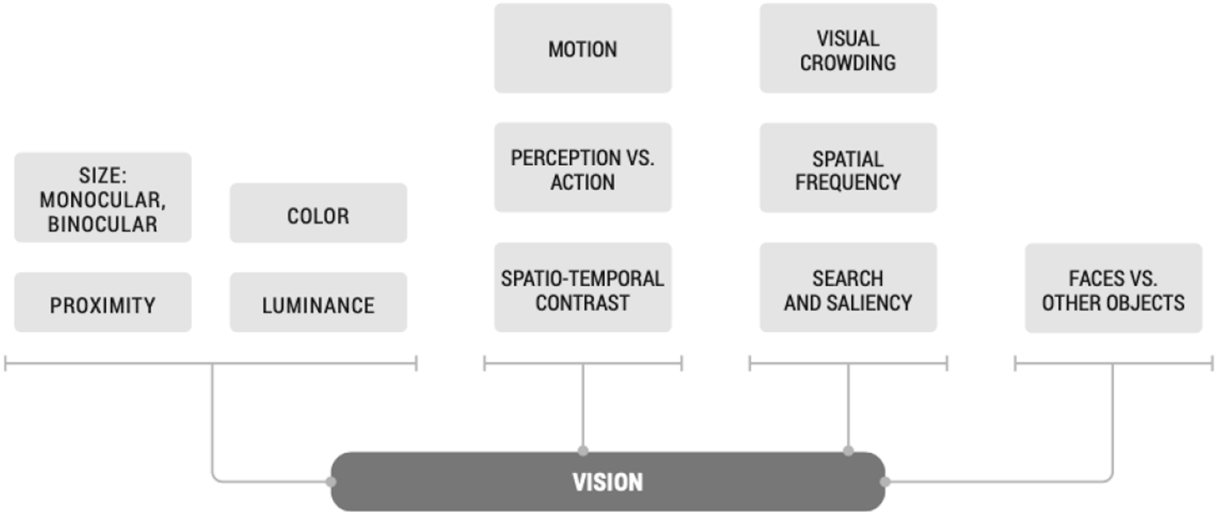

FIGURE 9
Neural pathways within the vision network.

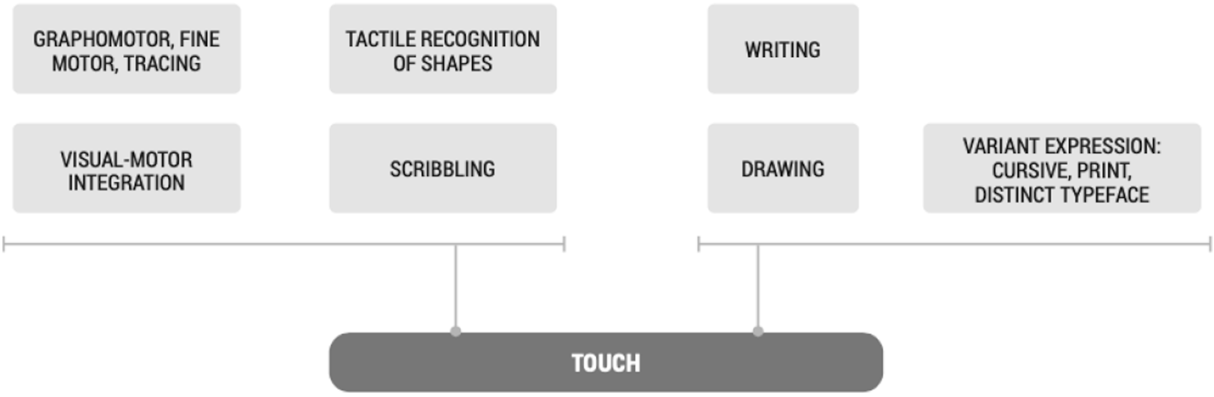

FIGURE 10
Neural pathways within the touch (haptic) network.

Broadbent and Mareschal, 2019; Tokuhama-Espinosa, 2019; De Soto, 2022). To further explain Radical Neuroconstructivism, we incorporate the concept of Meaning Making (Postman and Weingartner, 1969; Gay, 2018; Immordino-Yang and Knecht, 2020; Nouri et al., 2022) and Core Notions as the fundamental building blocks of cognition (Skerry and Saxe, 2016; Rist, 2017; Hernández Armenta et al., 2019; Solis-Stovall, 2020; Tuominen and Kallio, 2020; Sporns, 2022). We also provide examples of Math and Language learning trajectories that can be designed using neuroconstructivist principles, with more than 100 sources supporting each trajectory. Each of these studies holds individual significance and, when synthesized, we consider them to establish a powerful foundation for the proposed theory. We propose that the theory of Radical Neuroconstructivism offers a new framework for teacher education.

We suggest that teacher education can be seen as a holon, a complex system that consists of different parts that are interrelated and interdependent. However, not all parts of this system have received equal attention from academic disciplines such as psychology and education. While the question of *how* to teach has been widely researched, followed by the question of *what* to teach, the *why* of teaching has been less explored. This is where Mind, Brain, and Education (MBE) science can offer valuable insights. In Figure 11, in the first panel (Figure 5 "From Invisible Core Notions to the Visible Educational Curriculum"), the child learns the core notions in their own brain, but that same child (second panel) interacts with other children and the teacher. This dynamic exchange in the classroom is combined with the genetics, social-economic status and cultural context of the learner (third panel).

Evidence from MBE science can integrate the different subparts of teacher education by providing a better understanding of the *why*, which has been often neglected in traditional educational and psychological approaches. Radical neuroconstructivism is one framework that can inform teachers' professional development and complete the holonic perspective of teaching.

In relation to the *how* of teaching, radical neurosconstrutivism suggests that teachers should encourage active exploration and

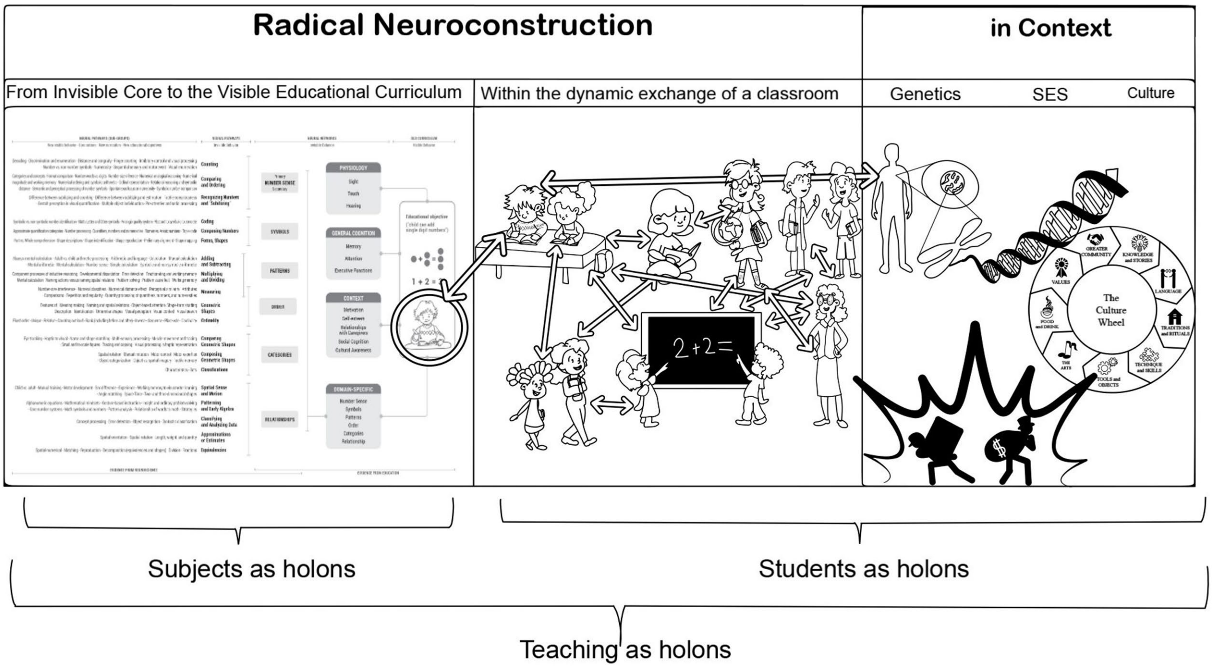

FIGURE 11
Radical neuroconstructivism in context.

discovery in their students, rather than transmitting information passively. This approach allows students to engage with the material in a meaningful way, and to construct their own representations based on prior knowledge and experience. Evidence as to why this is important suggests that active exploration can improve students' motivation, curiosity, creativity, and memory retention.

Regarding the *what*, radical neuroconstructivism suggests that teachers should be aware of students' developmental trajectories and individual differences, and tailor instruction accordingly. Teachers should identify difficulties and provide appropriate scaffolding and support to help students overcome them. Moreover, teachers should integrate different domains of learning in their curriculum to facilitate the formation of more abstract and generalizable representations, as well as the transfer of skills and knowledge across contexts.

To extend this perspective to the *why*, teachers need a solid understanding of core notions and the trajectories through which neural networks are constructed. This approach improves the order of skill acquisition by using a neuroconstructivist hierarchy, which may help create a more orderly curriculum built on insights from MBE science. Compared with MBE advancements from 2007 to present, by integrating research from neuroscience, psychology, and education, this new idea has the potential to inform the design of curriculum and instructional strategies that not only consider the what and how of teaching, but also the why, ensuring alignment with the brain's natural learning processes.

In conclusion, MBE science offers a hol(on)istic perspective on teacher education that takes into account the *what*, *how*, and *why* of teaching and learning. Radical neuroconstructivism is a useful framework for organizing teachers" professional development and applying insights from MBE science into curriculum design and instructional strategies. By using MBE science to inform teaching practices, teachers can create a more effective and engaging learning environment for students.

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

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

Acknowledgments

The authors wish to thank people who have offered feedback on various versions of this manuscript between 2013 and 2023, especially Mariana Rivera who assisted in the original research in 2013.

Conflict of interest

Authors TT-E and CB provide consultancy services via the Conexiones platform. Author CB is employed by The Decision Lab.

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TYPE Original Research
PUBLISHED 03 August 2023
DOI 10.3389/fpsyg.2023.1232315

Check for updates

OPEN ACCESS

EDITED BY
Lorna Uden,
Staffordshire University, United Kingdom

REVIEWED BY
Eleni Mitsea,
National Centre of Scientific Research Demokritos, Greece
Stamatios Papadakis,
University of Crete, Greece

*CORRESPONDENCE
Rivi Frei-Landau
✉ rivipsy@gmail.com

RECEIVED 31 May 2023
ACCEPTED 18 July 2023
PUBLISHED 03 August 2023

CITATION
Frei-Landau R, Grobgeld E and Guberman R (2023) Implementing digital neuroscience in special-needs-teacher education: exploring student-teachers' multifaceted learning outcomes related to teaching children with neurodevelopmental disorders.
Front. Psychol. 14:1232315.
doi: 10.3389/fpsyg.2023.1232315

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Implementing digital neuroscience in special-needs-teacher education: exploring student-teachers' multifaceted learning outcomes related to teaching children with neurodevelopmental disorders

Rivi Frei-Landau[1]*, Etty Grobgeld[2] and Raisa Guberman[3]

[1]The Rehabilitation Psychology Program, Faculty of Psychology, Achva Academic College, Arugot, Israel, [2]The Neuro-padagogy Centre, Achva Academic College, Arugot, Israel, [3]Department of Mathematics, Achva Academic College, Arugot, Israel

Introduction: In recent decades, there has been increased use of neuroscience in teacher education, which refers to applying knowledge from brain science to teaching. Similarly, digital learning has been extensively integrated into teacher education, particularly in light of the COVID-19 pandemic. However, the benefits of assimilating educational neuroscience into special-education training—particularly using digital platforms–have yet to be examined. The current study explored the use of digitally-delivered educational neuroscience, related to neurodevelopmental disorders (ND), in teacher education, to gain insight into the learning outcomes alongside the contribution of the digital platform.

Methods: Employing a qualitative approach, we recruited 193 student-teachers who learned a digital ND-related neuroscience course. Data collection included open-ended reflections, open-ended story questions and five focus groups – all of which were analyzed using content analysis.

Results: Findings revealed a process involving four learning outcomes: understanding brain-based mechanisms of ND, enhanced empathy, extended perception of teachers' professional role, and the design of pedagogical adaptations. The analysis also pointed out the various ways in which the digital platform facilitated these learning outcomes.

Discussion: The study provides theoretical insight into the role of digitally-delivered educational neuroscience in the service of inclusion. It further discusses the practical implications of using digitally-delivered educational neuroscience in teacher education to promote an inclusive pedagogy and best practices.

KEYWORDS

digital learning, educational neuroscience, brain-based learning, neurodevelopmental disorders, inclusion

Introduction

In recent decades, there has been increased theoretical interest in the connections between the mind, brain, and education (Wilcox et al., 2021; Gola et al., 2022). As a result, a new field of research developed, which is referred to as educational neuroscience, neuropedagogy, or neuroeducation (Uden and Guan, 2022). This new field applies the findings of brain research to classroom teaching and learning, in general, and to teaching various K-12 teachers and students, in particular (Ansari et al., 2011; Brown and Daly, 2016; Thomas et al., 2019). Similarly, the education system had to adapt to the twenty-first-century developments in the digital field (Hsu, 2016; Geri et al., 2017; Mitsea et al., 2021, 2023). As such, the integration of digital technologies into schools and academia required the development of a new pedagogy in teacher education (Koehler and Mishra, 2008), which then could be adapted to suit the various content disciplines (Cui and Zhang, 2021). Recently, this need for a unique pedagogy became even more urgent, as the world coped with the transition to digital teaching due to the COVID-19 pandemic (Ching and Roberts, 2020; Frei-Landau et al., 2022a; Muchnick-Rozanov et al., 2022b; Hershkovitz et al., 2023). Although digital learning and neuroeducation have been explored separately, the use of digital educational neuroscience—particularly in the context of special education—has yet to be addressed. To address this research gap, the current study examined the outcomes of learning an Educational Neuroscience course focused on Neurodevelopmental disorders (ND) to student-teachers (STs) using a digital platform.

Theoretical background

Educational neuroscience in teacher education

Educational Neuroscience is an emerging multidisciplinary field that integrates knowledge from behavioral sciences, cognitive psychology, neuroscience, and pedagogy, and it is defined as a subfield of education, neuroscience, and intelligence (Sousa, 2010; Knox, 2016; Vaughn et al., 2020). It is an interdisciplinary research field that seeks to translate research findings on neural mechanisms into educational practices (Uden and Guan, 2022). Although some argue that the core claim of educational neuroscience is that neuroscience can improve teaching in the classroom (Suresh et al., 2021), others claim that there are no current examples of neuroscience motivating new and effective teaching methods, arguing that neuroscience is unlikely to improve teaching in the future (Bowers, 2016). Hence, more research that unfolds this issue is needed.

Studies have noted that the teaching of Educational Neuroscience can lead to an in-depth understanding of processes of learning and memory (Goswrami, 2012); this understanding helps improve teaching, as well as classroom management strategies used by teachers (Brown and Daly, 2016; Howard-Jones et al., 2016), which in turn can lead to significant and effective in-class learning processes (Tokuhama-Espinosa, 2018). It was also argued that educational neuroscience may facilitate the design of interventions for improving executive functions (Cherrier et al., 2023). Considering these findings, teacher-education schools, colleges, and departments in academic institutions have begun to include courses in educational neuroscience in their curricula and explore their impact (Friedman et al., 2016, 2019; Guberman et al., 2022). For instance, Friedman et al. (2016) reported on pedagogical applications based on neuroscientific approaches, which can be applied to learning and teaching processes in the classroom. Examples of such pedagogical applications include teaching models; repetition, memorization, and memory solidification; previewing the lesson to enhance learning and teaching; using emotions to draw attention; harnessing the relationship between movement and learning; and increasing learning efficacy by organizing the learning processes to correspond to the learners' circadian cycle. Another recent study (Guberman et al., 2022) showed that elementary-school mathematics teachers applied the neuroscientific theory of mathematical cognition in their classroom practices after participating in a neuroscience professional-development course. Specifically, they demonstrated that the teachers acquired knowledge about neuroscientific theories and integrated their newly acquired knowledge into their teaching.

However, the benefits of assimilating neuroscience into *special-education* curricula—particularly using digital platforms—have yet to be examined. Considering the ongoing trend of the inclusion policy (as reflected in amendment 11 of Israel's Special-Education Act, 1988), a growing number of children with ND attend regular classrooms. As such, it is necessary to educate teachers on how to best interact with them and how to build best practices for them. It is further necessary to explore how exposure to educational neuroscience specifically related to children with ND affects teachers' learning. Hence, the current study explored the benefits of integrating educational neuroscience related to NDs in special-needs-teachers' training, to gain insight into the learning outcomes. However, this course was delivered digitally, using a novel teaching platform that has yet to be used in the context of teaching educational neuroscience.

Digital learning and teacher education

Digital learning enables teachers to teach students using a remote scenario (Carrillo and Flores, 2020). Digital platforms have become critical components in teacher education, as they allow for innovation and contribute to the learning process (Zadok and Meishar-Tal, 2015; Frei-Landau and Avidov-Ungar, 2022; Frei-Landau et al., 2022a). Specifically, the flexibility of digital tools helps teachers keep content up-to-date, elaborate on specific topics and address students' individual learning needs (Heemskerk et al., 2011). In fact, long before the COVID-19 pandemic, digital learning was increasingly used in teacher education and scholars had explored its processes and outcomes (Kleinsasser and Hong, 2016). However, the COVID-19 pandemic highlighted the need to employ digital learning, in general, and in teacher education, in particular, in times of crisis (Ching and Roberts, 2020; Muchnik-Rozanov et al., 2022). A recent literature review of 134 studies, on the use of digital learning in teacher education during the pandemic revealed that one of the most researched topics was the effectiveness of the teaching-learning process and its outcomes (Carrillo and Flores, 2020).

Generally, studies that examined the efficacy and characteristics of teaching in a digital environment have indicated that many aspects of the learning experience improve (Luterbach and Brown, 2011). For example, it was found that an environment enhanced with innovative digital-based technologies promotes active learning, increases learners' satisfaction with and pleasure from learning (Davidovitch and Yavich, 2017), and promotes significant and effective learning (Zadok and Meishar-Tal, 2015). Furthermore, research has also shown that digital learning has led to improved learning outcomes. However, it should be noted that at the same time, some studies emphasized the limitations of digital learning, claiming that the digitization of learning is more time demanding and hence is burdensome to the learner, which in turn might decrease the quality of the learning experience (Makransky et al., 2019).

Several advantages of the digital learning environment are mentioned in the literature. These include the option to work individually or cooperatively, exposure to materials and practice suited to the learner's pace and times, immediate access to data and feedback, and the availability of visual media (Caspi and Blau, 2011; Forkosh-Baruch and Hershkovitz, 2012). Furthermore, the digital learning environment is supported by numerous instruments and study aids that can enhance the depth and breadth of learning, among them multimedia items, consultation forums, visual enrichment materials, videoconferencing, a shared whiteboard, document sharing, messages and blogs, as well as tools designed to assist learners with special needs (Irene and Athanasios, 2023), such as programs for voiced reading and input. These digital tools can be adapted for use with various media types (written, oral, or visual), which thus serve to enhance and vary the learning outcomes (Blau et al., 2018; Kurtoğlu and Karal, 2023). Learning outcomes are defined as the combination of knowledge and abilities acquired by learners after participating in a structured learning process, such as an academic course, and may include knowledge, skills, understanding, abilities, and attitudes acquired by the learners (Anderson et al., 2001; Wang et al., 2023).

Digital technology and special-needs education in the context of neurodevelopmental disorders

In recent years the use of technology and digitalization in special needs education has become more frequent, particularly in the case of neurodevelopmental disorders (ND). ND represent a new diagnostic category in the Diagnostic and Statistical Manual of Mental Disorders, 5th Edition (DSM-5; American Psychiatric Association, 2013), that includes a group of disorders that commonly begin in childhood and have a neurological basis and therefore require special needs education and adjusted teaching. ND include intellectual disability, attention-deficit/hyperactivity disorder (ADHD), autism spectrum disorder (ASD), specific learning disorders (i.e., learning disabilities, involving difficulties in reading, writing and arithmetic), motor disorders (such as Tics, Tourette etc.), among others (Francés et al., 2022). As such, scholars and policy makers representing an inclusive worldview have recently advocated for the implementation of inclusive pedagogy, which represents an approach that addresses interpersonal differences among learners with special needs without excluding them from the mainstream classroom (Spratt and Florian, 2015; Kurtoğlu and Karal, 2023). This innovative approach was developed in an attempt to address the needs of learners for differential support without treating them differently from their peers in the classroom (Florian and Beaton, 2018). Hence, it focuses on ways to promote—and train teachers to adopt—a teaching approach that includes all learners while addressing their unique needs.

Correspondingly, recent studies have explored the use of emerging technologies for facilitating best practices as well as teacher-student interactions, to provide educators with new opportunities for intervention, especially for children with NDs. For instance, Mitsea et al. (2022a,b,c) have used cutting-edge digital technologies to practice skills in special education, such as training individuals with autism and/or learning disabilities to use metacognitive skills (Mitsea et al., 2022a,d), arguing that soft skills and metacognition are inclusion amplifiers (Mitsea et al., 2021). Similarly, virtual reality games were used to practice meta-skills in special education (Drigas et al., 2022; Mitsea et al., 2023) and simulations were used to enhance empathy towards children with special needs (Frei-Landau et al., 2022b; Frei-Landau and Levin, 2022c). In this vein, the current study focused on exploring the learning outcomes of a digitally conveyed educational neuroscience course related to ND attended by STs. We further sought to understand whether and how the learning outcomes were related to the digital platform. As such, the following research questions were formulated:

Research questions

1. How do STs perceive their learning outcomes in the process of learning and participating in the digital course in educational neuroscience focused on neurodevelopmental disorders?
2. In what ways did the digital platform facilitate STs' acquisition of these learning outcomes?

Methodology

The study context

In 2016, a Center for Educational Neuroscience was established in a major teacher-education college in Israel headed by Professor Friedman. The Center launched the first pilot course for 26 students enrolled in a Master of Education program, and its outcomes were reported by Friedman et al. (2016). The current study was held at this Center for Educational Neuroscience.

The structure and contents of the digital neuroscience course

The first author, which is also the head of Special-Education department at the college, designed an online course (titled Brain, Learning, and Special Education) that dealt with neurological aspects of learning and teaching that can be relevant for use with special-education populations, mainly for children with learning disabilities, attention deficit disorder, autism spectrum disorder (ASD), or cerebral palsy (CP). Accordingly, emphasis was placed on aspects of neuroscientific knowledge applicable and relevant to learners with special needs, who are often included in mainstream classes in the school system. On a pedagogical level, the course dealt with neuroscientific aspects relevant to teaching and learning processes, while taking advantage of the variety of tools and teaching methods available in the digital learning environment, among them interactive assignments, cooperative learning using a digital forum, video clips, and exercises accessed through links to various Internet sites, use of multimedia items, and the combination of synchronous and asynchronous digital lessons.

As regards the course contents, presented in Figure 1 below, the course included seven units, beginning with a preliminary introduction to the structure of the brain, its development, and functions. Each of the next six units dealt with a specific cognitive function, the brain regions that mediate this function, and the ND

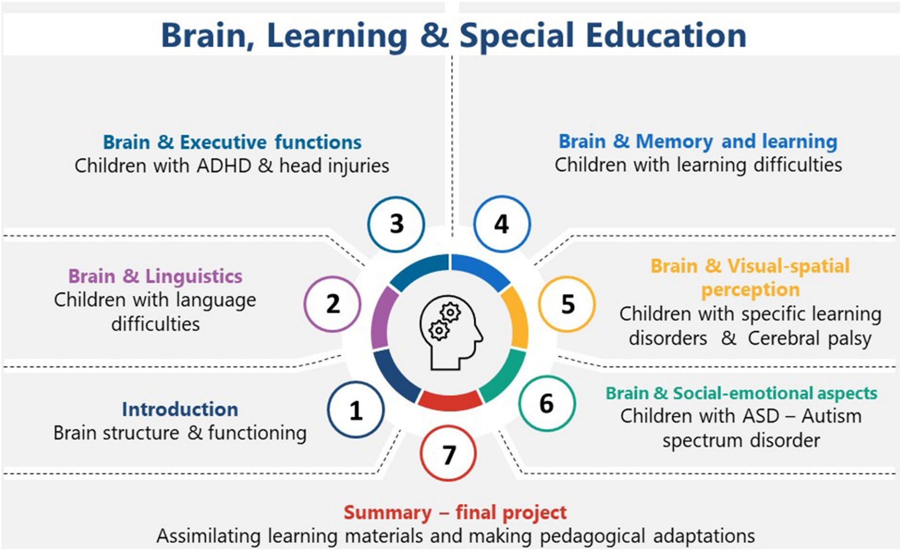

FIGURE 1
The structure of the course titled brain, learning, and special education, the study units, and the population of learners for which the unit and the corresponding brain functions are most relevant.

population that may be affected. Thus, for example, unit 2 dealt with unique diverse processes of the two hemispheres, their relation to language functions and to delayed language development or retrieval difficulties; unit 3 described the frontal lobes and executive functions and was discussed in the context of the needs of learners with attention deficit hyperactivity disorder (ADHD) or learners dealing with the effects of mild head injuries; unit 4 dealt with memory processes and was related to difficulties with work memory among children with learning difficulties and specific learning disorders; unit 5 dealt with visuospatial perception from a neural perspective and concerning spatial perception and analysis among learners with CP or learning disabilities; unit 6 dealt with the socioemotional functions and the regions that mediate them, and was related to the functioning of learners with ASD or with neurodevelopmental deficits resulting in social dysfunctions; unit 7 provided a review and summary of the course, including a final project. The current study describes the learning outcomes of STs who participated in this digital course, based on data collected over five academic years.

The study design

Exploring a phenomenon, such as STs' subjective learning experiences, calls for a qualitative methodology that captures the multifaceted nature of the phenomenon from the individual's standpoint (Creswell and Poth, 2016). A case study design (Stake, 2005) was selected as a viable framework for exploring the research questions, as it allows for an in-depth investigation of the observed phenomenon within the particular professional learning environment at hand (in this case, the learning outcomes of learners exposed to digitally-delivered education neuroscience). Throughout the 5 years of data collection, the courses shared the same content, as shown in Figure 1. Thus, are all considered a case.

Participants and data collection

The study participants included 193 students who attended the (specific) College of Teacher Education in Israel and—as part of their undergraduate study program—had been enrolled in one of the courses on Brain, Learning, and Special Education offered within the 5 years designated for data collection (2018–2022). The majority of the study participants were enrolled in the Department of Special Education (71%), while the remainder were enrolled either in the math-education department, in a national program for excellent students (11%); the early-childhood education department (9%); the English-teaching department (5%); or a different department (4%). Of the study participants, 87% were women and the remainder were men (a gender tendency common in education departments).

Data were collected using multiple data sources, to provide a comprehensive understanding of the explored phenomenon (Bogdan and Biklen, 1998), achieve trustworthiness through the triangulation of research methods, and enable cross-validity checks (Patton, 2002). Additionally, we conducted member checks—a frequently used method in qualitative inquiry (Frei-Landau et al., 2020c), to further support the study's trustworthiness (Birt et al., 2016). The following modalities were used to collect the data:

1. *Participants' post-course reflections*. At the end of the course, the STs handed in written reflections about their learning experience, the learning outcomes, and the manner in which the digital nature of the course affected the latter. They were asked to freely elaborate on their learning experiences and were encouraged to describe whatever issues they found relevant.
2. *An open-ended story question*: During this reflection, the STs were asked to answer two open-ended questions: The first requested that they elaborate on their learning insights and the second that they share a story related to their teaching experiences in schools (while learning the course) that reflects

their learning from the educational neuroscience course. Overall, 193 reflections were collected.

3. *Focus groups*. As the last step of the research data collection, we held five focus groups (one each year) with participants who agreed to take part in it. During the focus group, the participants were requested to discuss their learning experiences and to respond to others' comments about them. The focus group session lasted 45 min and was recorded and then transcribed.

Ethics

The study was approved by the institutional ethics committee. The participants gave their informed consent. Personal information was concealed, thus ensuring participants' anonymity; hence, when reporting the findings, pseudonyms are used. Participation was voluntary and participants were told they were allowed to refuse participation without risking any consequences.

Data analysis

Braun and Clarke's (2006) six-step inductive thematic analysis was used to analyze the interview contents. First, there was an initial reading and rereading of the transcripts, to become immersed in the data and to familiarize ourselves with the STs' experiences. During this stage, each reader worked on her own to make a note of key statements pertaining to STs' learning outcomes. In stage two, initial codes were generated separately by each coder across all data sets. This was followed by a discussion that sought to identify the most significant codes pertaining to teachers' learning outcomes. This microanalysis was used to ensure that no important ideas or constructs were overlooked. In stage three, once all the data had been coded, the codes were classified into potential themes, through a process of comparison and contrast conducted to identify patterns and overarching themes. In the fourth stage, these themes were reviewed and refined to ensure internal homogeneity and external heterogeneity. The data were then reviewed once again, to ensure that the identified themes were comprehensive and properly supported and grounded in participants' responses. In the fifth stage, the themes were yet again "refined and defined" (Braun and Clarke, 2006) through elicitation of the "essence" of each theme, and by giving them concise and mutually exclusive names. Finally, the sixth stage enabled the identification of those aspects that highlighted the studied phenomenon—STs' multidimensional learning outcomes, which rendered four major learning outcomes derived from the learning process. It should be emphasized that data were coded and analyzed by independent coders (the authors), followed by recurrent brainstorming sessions. Cases of disagreement were discussed and settled through conceptual clarification and consensus.

Trustworthiness

While qualitative inquiry does not traditionally claim to produce "absolute truths," it can instead strive to achieve what is known as "trustworthiness" (Korstjens and Moser, 2018) and "transferability" of the findings, which refers to the possible applicability of their results in other social contexts (Rodon and Sesé, 2008; Pratt and Yezierski, 2018). To this end, "investigator triangulation" was performed by two researchers during the coding, analysis, and interpretation of the data. Moreover, member checking was conducted, and participants' comments were embedded into the findings. Finally, the authors engaged in critical self-reflection and examined their own preconceptions, feelings, and values (i.e., representing the principle of reflexivity) and the ways in which these might have affected their interpretations of the materials.

Findings

The learning outcomes (RQ 1)

Analysis of the findings indicated four types of learning outcomes reported by the STs following their participation in the digital course in educational neuroscience. All four learning outcomes involved both perceptual changes and emotional experiences. These outcomes were related to their role as teachers, and to their observations of their students' experiences, as learners with ND. As displayed in Figure 2, these four learning outcomes evolved along a developmental process from "self to the other," as follows: it begins with understanding brain-based mechanisms related to ND; followed by enhanced empathy towards students with ND and their resulting challenges. This cognitive and empathic shift was accompanied by a change in STs' perceptions of their role as teachers. The learning process ended with them making practical pedagogical adaptations to their teaching techniques, according to the educational neuroscience knowledge they acquired.

The following section includes a description of the learning outcomes using the quotes from STs. All names are pseudonyms.

Understanding brain-based mechanisms related to ND

The participants described an enhanced understanding of brain-based mechanisms of ND, following their participation in the course, which eventually was experienced as the ability to better facilitate inclusion.

> The course was enriching, and with five years of homeroom teaching experience, while learning some of the units, I suddenly saw before me some of my former students and especially one who this year is clearly having a hard time. Now I know how to name her difficulty. That gives me a good feeling … I simply have a better understanding now.

This is one example among many, in which the STs reported an enhanced ability to understand the difficulties and challenges of learners with ND, which gave them a sense of relief and was received as a fascinating experience:

> Now I can explain much of the phenomena I see in the children with whom I work in special education … I have some experience working with children on the autistic spectrum…. The theoretical knowledge provides an explanation for what I am constantly

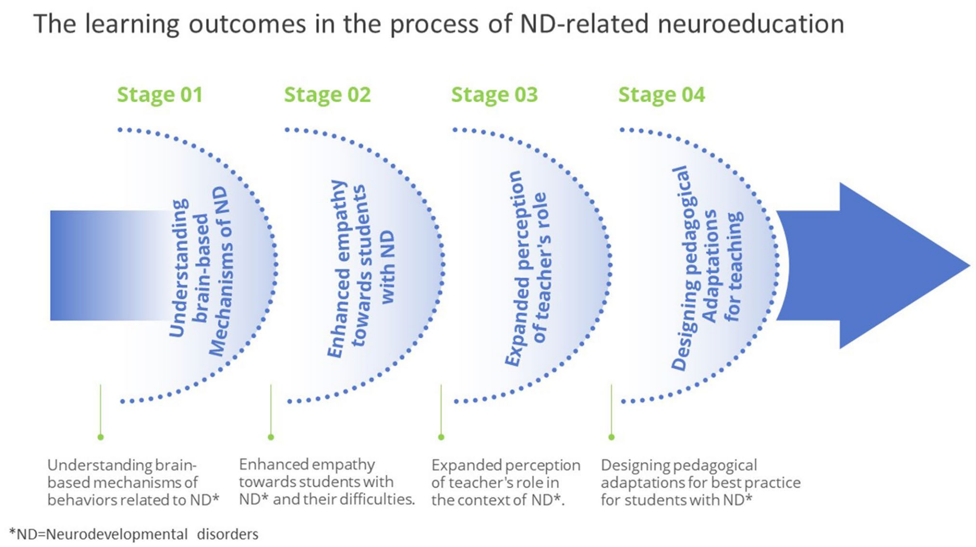

FIGURE 2
The study's model—four learning outcomes.

> witnessing and that is fascinating. For example, I can see that my student Tom (pseudonym) has difficulty predicting and understanding the behaviors of others. Now I understand the root of the social difficulties these students.

One of the STs who worked with children with behavioral problems explained that by understanding the brain mechanism, she is able to promote the child's inclusion, which in turn leads to the child's improved abilities. Thus, the process is respectful of the child and his or her needs.

> As a homeroom teacher in a school for children with behavioral problems, this unit helped me understand that the root of their problem is deficient emotional regulation. For example, a child was frustrated and has a hard time regulating his reactions and consequently may demonstrate impulsive and violent behaviors. However, this is due to a delay or deficiency in the response of the prefrontal cortex to the stimulus that comes from the amygdala. Knowledge is power! In the context of teaching children with special needs, this knowledge can make the difference between momentary assistance and real progress and inclusion in society. Without understanding the theoretical background, one is more likely to make repeated mistakes and miss opportunities to help students advance.

Developing enhanced empathy towards children with ND and their difficulties

Developing empathy and acceptance were described by the participants as a major and significant learning outcome of participating in the course. Participants reported feeling greater empathy towards specific populations, such as children with late verbal development, ADHD, or learning disorders and claimed that this empathy emerges as the teacher becomes aware of the source of the child's behavior in the classroom.

> The findings presented in the current course were eye-opening and made us more aware, able to understand more, and be more accepting. In general, I think that I will be more understanding, for example, when a student with a learning disability is unable to organize or prioritize tasks.

Furthermore, it appears that there is a shift in the STs' attributional thought patterns related to a child's behavior, from an internal negative attribution (the child's disruptive behavior is intentional) to an external attribution (the behavior is caused by a neurological deficit or difficulty).

> Once we learned about the different parts of the brain and the differences (between the typical and atypical brain), our perception of students who are disruptive or behave unexpectedly can shift. We understand that sometimes the student has no control over these things…. For example, I understood the difficulties encountered by students with ADHD in terms of their executive functions, which can result in behaviors that antagonize teachers. But now I truly understand that it is a real challenge for them. I understand why the student may be disruptive or have difficulty and that it is not voluntary.

This perceptional change in thought patterns enabled the STs to accept the divergent behavior of learners with special needs and feel empathy toward them. As a result, they demonstrated greater patience, and their increased empathy motivated their desire to make the necessary pedagogical adaptations to help these children learn.

> I wasn't aware of the connection between ADHD and executive functions. The activity on the site with the clip showing children's behaviors left a strong impression and made me understand a little more of what these students feel; it gave me a sense of what I can

> do to draw their attention. For example, giving brief and clear instructions gradually one stage after another; allowing them to move about as needed (because it is truly a necessity); believing in their ability and conveying this belief to them; and in general, demonstrating flexibility.

Another student specifically mentioned that this "eye-opening" that causes empathy results in better inclusion: "The information presented in the course was eye-opening and led us to pay closer attention, which enabled us to understand and better accept the students' behaviors."

Professional identity change—an expanded perception of the teacher's role

The course participants described changes in their professional identity, with an emphasis on the expanded perception of the teacher's role. They described changes related to two aspects: the first was a change in their role perception (which may have emerged following their new sense of empathy); specifically, they realized that the teacher's role is not limited to conveying information but also includes establishing a learning atmosphere that is respectful and enabling.

> I come from teaching mathematics as a discipline, through the program for excellent students, so I have no background in special education…. But I learned that as a teacher, I must make the material accessible to learners with attention deficit or learning disabilities and that this should be done calmly and patiently, avoiding cynicism at all costs, by nurturing a positive learning atmosphere in the classroom.

As seen, participants came to realize that the teacher's role extends beyond teaching the material and also includes creating an enabling atmosphere in the classroom. The second aspect in which STs' role perception shifted was in understanding that the teacher is obligated to make adjustments to the learners' needs, using pedagogical tools and, furthermore, that this obligation is rooted in understanding the differences among learners and their needs. The participants' reports indicated that their expanded role perception coincided with a greater motivation and willingness to make pedagogical adaptations in their teaching methods, to cater to the learner's needs.

> I feel that the material we learned helped me gain profound insight into the source of students' learning disabilities and to internalize the understanding that as teachers, we are expected to adjust the assignments we prepare so that they are clear also to learners who have difficulty reading. Now, I not only know that this is necessary but I also understand why it needs to be done.

Another shift in their role perception came as the revelation that the teacher who understands the cause and character of the deficiency can have a positive effect on the learner's self-image:

> I understood that children who have difficulty with executive functions experience difficulties in getting organized, planning and solving problems, and in monitoring processes. All of these have a negative effect on their self-image. Hence, as teachers, we can have a strong influence on them, by adjusting how we respond to and address their difficulties. A helpful response can help increase the students' confidence and self-image.

Another ST noted the following: "By trying to identify the student's strengths and thought patterns, we can help leverage the strengths and create an experience of success; understanding how the brain works can help empower the learner." This ST clearly states that understanding the workings of the brain helped her make the necessary adjustments in her attitude and responses, which can lead the student to experience success and empowerment.

Designing pedagogical adaptations for teaching

A large proportion of the participants' reports referred to the need to produce practical pedagogical applications as one of the important outcomes of participating in this course.

> I have learned to notice learners with organizational difficulties. I will be sure to teach learning strategies, and thus help students organize the material in their minds; I can help them set goals that they can accomplish and help them organize their activities within time constraints.

More specifically, the STs learned to identify symptoms of learning disabilities, which led them to attend to the adaptations that need to be applied: "For example, for children with difficulties in visual perception, I have come to understand how this learning disability affects the student. I now know how to adjust the learning process for these students." A similar outcome reported was the ability to make adaptations to correspond to the needs of the various populations reviewed in the course (learners with ASD, learning disabilities, ADHD, etc.). Moreover, as a result of participating in this course, the participants described their decision to focus on students' needs in the framework of their practicum, as the following example demonstrates: "Part of my job is to teach children with ASD. The unit about developing empathic abilities led me to work with my students on the issue of empathy."

STs described various pedagogical adaptations that coincide with what they learned, as demonstrated in the following:

> As part of our English lessons, we read the play All My Sons. My student had a very difficult time understanding the complex relationships described in that work; he managed to understand the plot but not what was motivating the characters or their behaviors. So I presented a version of the play in the form of a comic strip, which added a visual layer. In addition, we interpreted the work in a very concrete manner, without relating to the subtext.

Another ST described the pedagogical adaptations she made in her teaching as a result of the course:

> I found that the section on the frontal lobes and the executive, monitoring and control functions that affect attention helped me a great deal in my work with children with attention deficit and behavioral problems. I emphasized the issue of self-organization and management, both in the classroom and during recess.

> I began by addressing pupils' preparations before class, i.e., taking out their notebooks, pencils and pens, the sequence of required tasks, and then went through a variety of social situations in the classroom that occur daily and addressed proper ways to cope with each situation, e.g., waiting for your turn, accepting the rules of the game, solving problems without violence, etc.

The role of the digital environment in promoting the learning outcomes (RQ 2)

The second research question examined the contribution of the digital platform to producing the learning outcomes. Analysis of the findings demonstrated that the STs reported a variety of ways in which the digital nature of the course enhanced the learning outcomes in each of the categories mentioned. Thus, for example, they reported using the study aids available on a website, the many study tools they could access, the availability of additional texts and visual clips, and the use of a forum for sharing with each other, as aspects that contributed to the development of the learning outcomes.

As follows are selected quotes demonstrating aspects of digital learning that promoted the learning outcomes:

Understanding brain-based mechanisms of ND

> The tools on the website, all of the exercises and examples, as well as references to external websites, helped me gain an in-depth understanding. It suddenly made things clearer. I plan on keeping some of the course materials. The activities available online were very helpful.

As this example demonstrates, the STs described in detail the way the digital aids enhance their understanding of the material studied, i.e., the NDs. It appears that the online environment, the visual aids and the various exercises, helped the STs internalize their new knowledge.

Enhanced empathy towards students with ND

> There were exercises on the website that increased my understanding…. For example, the figures … The examples provided…. The ability to share experiences from the practicum on the forum…. The demonstrations heightened my understanding of how my students feel, for example, the demonstration of how a child with a learning disability experiences the lesson was really eye-opening and meaningful. I understood that I need to exercise patience and sensitivity to accept and enable these students, to make them feel good and worthy of our belief in their abilities.

In this representative example, the ST notes that the digital demonstrations on the website provided an emotional experience that connected them with the experience of learners with NDs. This experience, in turn, aroused a new sense of empathy and understanding about the importance of accepting these students.

Expanding one's role perception as a teacher

> The activity on the website—regarding learners with difficulties in visual perception, provided a very impactful demonstration of the difficulties encountered by the learner and drove home my role as an educator in supporting their needs and finding effective teaching methods that work for them.

> The video clip and the exercise that followed, about learners with attention deficit, really demonstrated the degree of pressure that these learners feel, and I have understood that the demands made by the teacher and the school system only increase this problem. I learned that as a teacher, I must allow them the time they need and not urge them to hurry.

As these examples clarify, the digital demonstrations not only helped develop STs' sense of empathy towards their students with NDs but also raise their consciousness regarding their role as teachers, leading them to realize that it also includes helping students with special needs.

Designing pedagogical adaptations

> I learned a lot about practice in the field and the tools that I can use as an educator…. For example, when we learned about learners with attention deficits, the questionnaires and exercises that we learned were very helpful for identifying the learners' precise problems. I also liked what we learned about addressing these difficulties: the use of organizational charts for morning and evening activities. I will definitely use these and print them out for my work with the students. It taught me the type of things I need to notice in order to mediate verbally the goal or objective (as shown in the demonstration), and perhaps even to seek other ways to help them—to be creative about it.

Discussion

The current study examined the learning outcomes of a digitally-delivered educational neuroscience course related to children with ND. The study's findings highlight four types of learning outcomes reported by the STs following their participation in the digital course in educational neuroscience. These four learning outcomes evolved along a developmental process from oneself to the other, as follows: it begins with understanding brain-based mechanisms related to ND, followed by enhanced empathy towards students with ND and their resulting difficulties, which is then accompanied by a change in STs' perceptions of their role as teachers, and ends with them making practical pedagogical adaptations to their teaching techniques, according to the educational neuroscience knowledge they acquired. Hence, the current study affords an integrative view of the learning outcomes. The study also highlights the benefit of the digital platform in this context, by showing the variety of ways in which the digital nature of the course enhanced the learning outcomes in each of the categories mentioned. In this vein, this study further strengthens prior claims regarding the suitability of cutting-edge technologies for promoting best practices in special education. For instance, Mitsea et al. (2022a,b,c) have used cutting-edge technologies to practice skills in special education training, such as promoting metacognitive skills among individuals with autism (Mitsea et al., 2022a) or learning

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disabilities (Mitsea et al., 2022d). Similarly, Mitsea et al. (2022a,b,c,d) used virtual reality games to practice metacognitive skills among children with special education needs.

Digital neuroscience in the service of STs' professional development

The findings of the current study correspond with previous findings in this field, showing that educational neuroscience may affect teachers' professional development perceptions (Hachem et al., 2022) and contribute to best practices (Luque-Rojas et al., 2022). Thus, for example, in a previous study that interviewed teachers about their views regarding the relevance and advantages of educational neuroscience (Hook and Fara, 2012), the participants reported their interest and enjoyment of being intellectually involved in an innovative field and mentioned three learning outcomes: (a) enhanced self-confidence, professional control and authority; (b) a changed perception of and increased patience and empathy towards challenging students, in light of their understanding of the neurological processes that affect these students; and finally, (c) professional satisfaction and an improved self-image, caused by their understanding of the important role played by the teacher, namely, nurturing the mind and consciousness of the learner. Some of these learning outcomes were also identified in a sample of 80 graduate students who participated in a face-to-face course on educational neuroscience (Friedman et al., 2019). Specifically, the following four major themes emerged from the study's analysis of the participants' reports: (1) It is essential to apply basic neuroscientific knowledge in contemporary teaching practices. (2) Neuroscientific knowledge provides a conceptual underpinning to teachers' commonly used pedagogical practices, which enhances teachers' professional competence and confidence. (3) Knowledge of neuro-processes enables teachers to devise different pedagogical approaches and methods. (4) Gaining an understanding of different learners' neuro-functions can help teachers choose alternative approaches that are better suited to their students' needs (Friedman et al., 2019). Hence, the current study reinforces the findings of the two aforementioned studies while also honing our understanding regarding the broader role of teachers of students with NDs, which requires both a shift in teachers' perceived professional identity and the inclusion of empathy. However, in contrast to the previous findings, which emerged from studies involving courses taught face-to-face, the current study involved teaching via digital platforms, thus amplifying the implications of the previous studies, while demonstrating the benefits of using cutting-edge technologies.

Digital neuroscience in the service of inclusion

Inclusive pedagogy, which stems from an inclusive worldview, represents an approach that addresses interpersonal differences among learners in a way that refrains from either labeling learners with special needs or excluding them from the mainstream classroom (Spratt and Florian, 2015). This innovative approach was developed in an attempt to address the needs of learners for differential support without treating them differently from their peers in the classroom (Florian and Beaton, 2018). As a result, this approach focuses on ways to promote teaching that includes all learners while addressing the unique needs of each. Furthermore, the current study's findings indicate that STs' exposure to knowledge about the brain's functioning and mechanisms in learners with special needs motivated them to adopt and promote an inclusive pedagogy.

An interesting finding is related to the process of STs' attributions. Studies indicate that understanding teachers' cognitive perceptions regarding inclusion is essential. Specifically, teachers' beliefs, knowledge and attitudes about the mental functions that lead to special needs were found to play a major role in their classroom practices (Sherman et al., 2008). One such cognitive domain is teachers' attributions (interpretations) regarding the misbehaviors of students with ND.

The attributional theory (Weiner, 2000) conceptualizes one's interpretation of oneself and others' behaviors. It focuses on the causal explanations that individuals give when judging an event. These attributions are made along three dimensions: the locus of control, which addresses the question of who/what is responsible for the event (internal, external); stability, which assesses whether the situation will persist (stable, unstable); and controllability, which asks: Is it possible to control the event? (controllable, uncontrollable). Weiner (2000) has claimed that when an undesirable event is perceived as internal and controllable, individuals tend to place blame upon the individual, and thus perceive him/her as deserving an angry response, punishment and little sympathy. In contrast, perceiving the cause as external and uncontrollable (i.e., an illness, or a disorder) is associated with viewing the person as deserving of sympathy.

Applying the attributional theory to one's attributions for students with ND-related misbehaviors is interesting. For instance, studies have found that parents of children diagnosed with ADHD who attributed their misbehaviors to an internal locus, with stable and controllable causes (i.e., "He misbehaved on purpose. He always does that"), tended to display harsher and more negative discipline methods—which, in turn, predicted escalation in child's problem behaviors (Johnston and Ohan, 2005). Eventually, this may result in endorsing a more punitive, harsh and criticizing educational strategy (McAuliffe et al., 2009), impeding teachers from helping students to manage their behaviors (believing that it is under their control) and affecting teachers' implementation of helpful classroom practices (Mikami et al., 2019). This state of affairs often results in an escalation of undesirable behaviors; hence, these attributions are an important target for exploration, awareness and intervention. Correspondingly, discerning teachers' attributions when facing ADHD-related (or any other ND-related) behaviors in the classroom is essential (Mikami et al., 2019). The current study indicated that exposing STs to ND-related neuroeducation has the potential to shift their attributions, thus promoting better treatment and inclusion. This echoes the findings of a study that showed that using educational neuroscience in teacher training may facilitate teachers' understanding of neuromyths (Arslan et al., 2022).

In the same vein, a major finding that is particularly important in the context of inclusion is related to STs' report of increased empathy regarding the difficulties experienced by learners with ND. As mentioned, participants reported feeling more empathic toward students with ND-related difficulties. This enhanced empathy was related to their understanding of the neurological mechanisms, which was facilitated by the use of digital media and technology. This corresponds to a previous finding, which demonstrated that informed use of relevant media has the potential to enhance one's empathy towards others (Batson and Ahmad, 2009).

Ultimately, it appears that STs have experienced both cognitive, perceptual and emotional changes. Avni and Rotem (2013) claimed that learning becomes significant "When it is important, valuable, and meaningful to the learners and corresponds to their conceptual, cognitive, and emotional world, such that the learning experience fashions the learners' reality, personality, skills, development, and future." Accordingly, it may be assumed that it is likely that the changes reported by the learners in this study, which were related to both their emotional and cognitive worlds, would be internalized by the learners and applied in their future work as teachers.

Limitations and implications

Longitudinal studies over several years could further our understanding of the practical implementation of the knowledge gained over time, demonstrating whether these learning outcomes develop and/or change over time and with increased experience. In addition, it should be noted that all self-report measures may have been influenced by social desirability bias. Nevertheless, we believe that the triangulation of data sources helped minimize the chance of bias as much as possible.

Future research may opt to explore whether these learning outcomes manifest similarly or differently at teachers' different career stages and whether personal experience plays a role in this process. Finally, future research may be conducted among learners of various cultures and minority groups, as participants' background was found to be an essential factor affecting their adjustment in managing complex situations (Frei-Landau et al., 2020a,b).

In conclusion, the current study's findings demonstrate that using educational neuroscience in teacher education promotes and facilitates inclusion and that in this context, the digital platform has a beneficial role. Thus, this study contributes to the ongoing conversation about ways to advance STs' acceptance and use of inclusive pedagogies and best practices. This is imperative, given the current worldwide concern with the pursuit of social justice, manifested in the trend of including children with NDs in mainstream classrooms. The study also contributes to the ongoing debate on the benefit of implementing educational neuroscience in teacher education.

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 Achva Academic College Ethics Committee (2018_76), Israel. The patients/participants provided their written informed consent to participate in this study.

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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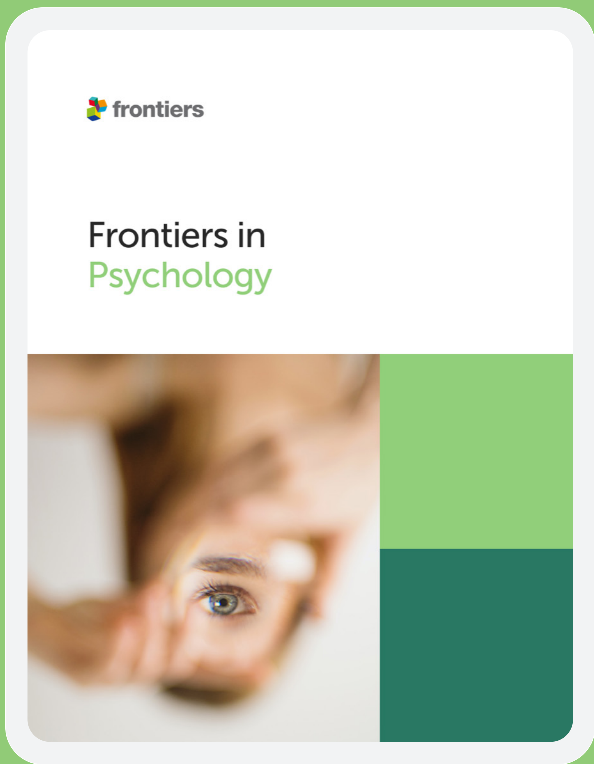

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