# NEUROSCIENCE, LEARNING AND EDUCATIONAL PSYCHOLOGY

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# NEUROSCIENCE, LEARNING AND EDUCATIONAL PSYCHOLOGY

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# Table of Contents

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# Editorial: Neuroscience, learning, and educational psychology

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Editorial on the Research Topic
Neuroscience, Learning, and Educational Psychology

Studying neuroscience within the educational context is a necessary effort and, in some cases, a mandatory one. However, an educational environment cannot be limited solely to the classroom; there is so much more, including, but not limited to, self-development, interactions, and relationships with the teacher. In this same line, it is essential to research studies that can provide us with rich, valid, and complete information from a neuropsychological perspective, particularly to the students within the context that defines them culturally, personally, familiar, and academically.

Advances in the contribution of neuroscience to education and personalization of learning could be the sentence that summarizes the main interest of publications in this Research Topic. The topic of Neuroscience and Education is already gaining attention as an emerging research field. Scientists are starting to discover that the relationships within the brain are strongly linked to improving abilities both within students and teachers. Despite limited research in Educational Neuroscience, it is a new and innovative area of study where we can find a large amount of development. These studies contribute significantly to discoveries and materials in this growing field.

Through this research, we want to delve deeper into the connection between Neuroscience and Education beyond just academic performance to avoid confusing classroom work with activities based on emotion, cognition, and motivation. Nowadays, we can see how the term neuroeducation is being used frequently without connecting it to the objective analysis of the brain and its multiple options in some educational contexts and schools. The current Research Topic collects 14 articles under world-leading authors from different specialization areas (Psychology, Neuroscience, Education, Pedagogy, and so on.). Articles published belong to four topics: Neuroscience, Education, Learning, and Educational Psychology (Table 1).

TABLE 1 Conditions of articles in the Research Topic.

| | Research methods | Journal | References | Data collection methods and tools | Study group |
|---|---|---|---|---|---|
| 1 | Exp | Psychology | Liu, Wang et al. | Behavioral<br>Skin conductance<br>Heart rate | 21–23 |
| 2 | Exp | Psychology | Zhao et al. | Behavioral | 15 |
| 3 | Perspective | Education | Macrine and Fugate | Behavioral/Technologies | – |
| 4 | Systematic Review-Meta-analysis | Psychology | De-la-Peña and Luque-Rojas | Behavioral | 18–25 |
| 5 | Brief Research Report | Psychology | De-la-Peña et al. | Behavioral | 17–47 |
| 6 | Exp | Psychology | Poon et al. | Behavioral | 8–10 |
| 7 | Exp | Psychology | Alhossein | Behavioral | Teachers |
| 8 | Exp | Education | Luu-Thi et al. | Behavioral | Teenagers |
| 9 | Exp | Psychology | Wang et al. | Behavioral | 23–35 |
| 10 | Exp | Psychology | Aranda et al. | Behavioral | University students |
| 11 | Exp | Psychology | Bartolomé-Anguita et al. | EEG<br>Behavioral | Young Adult |
| 12 | Hypothesis and theory article | Psychology | Liu et al. | Eye tracking<br>Electroencephalography recording<br>Behavioral | University students |
| 13 | Exp | Psychology | Shi and Qu | EEG<br>Eye tracking<br>Behavioral | Teenagers |
| 14 | Opinion | Psychology | Gola et al. | – | – |

With this particular Research Topic, we would like to present the original studies of Neuroscience in Education to the educational science community on studying the brain and their answers to Comprehensive Education (Personal, Social, Cognitive, and Emotional Development).

Considering the neuroscientific studies, Gola et al. indicated that educational neuroscience research "that invests at different levels the theories and practices of education are not new." However, we must focus on the different processes studied in this field, the biological perspective in education, and the relationship between cognitive processes (e.g., executive functions) and learning (e.g., stress and the difficulty of learning). Gola et al. also emphasized the use of neuroscientific techniques "into the psychological theory of educational constructs (such as reading)." In this sense, to measure the effectiveness of color-coding, Liu, Ma et al. used two neurophysiological tools: (1) eye-tracking, and (2) electroencephalography (EEG). Liu, Ma et al. showed that the color-coded design was more beneficial than the grayscale design (e.g., smaller pupil diameter), indicating changes in brain EEG activity (e.g., higher theta and alpha band power) and better learning performance. Moreover, Shi and Qu studied the effects of cognitive ability and self-control on comprehensive academic performance. They used several tools, including behavioral tests and neuroscientific tools, EEG, and eye-tracking. The results indicated a direct relationship between cognitive processes (memory, information processing, representation ability, logical reasoning ability, and thinking transformation ability) and self-control.

Similar to other studies on this Research Topic, the effects of collaborative learning were measured using psychophysiological techniques. Liu, Wang, et al. described the relationship between interpersonal physiological synchrony and collaborative learning activities while measuring electrodermal activity (EDA) and heart rate (HR) when students participated in lessons comparing synchrony between independent tasks and group discussion activities. Liu, Wang et al. indicated that high collaboration pairs gave significantly higher EDA and HR synchrony during the group discussions than low collaboration dyads. We can find another article (Bartolomé et al., 2022) that studied coaching as a human development tool using EEG and three experimental conditions: rumination®, directive (DC), and non-directive coaching (NDC). EEG indicated changes in alpha and theta frequencies in the right temporal region, and alpha, theta, and gamma in the right parietal region were measured in the NDC compared to R and DC conditions. The results were related to creativity and the development of human knowledge.

Along with the research of Liu, Ma, et al. and Shi and Qu, but under behavioral approaches and learning processes, Luu-Thi et al. demonstrated the link between mathematics anxiety and academic coping strategies, gender, grade, and career choices. Like Luu-Thi et al., de-la-Peña et al. studied attitudes toward mathematics and its relationships with other cognitive processes, like creativity and cognitive flexibility. The authors confirmed that details and cognitive flexibility were good predictors of a positive attitude toward mathematics. These results could have implications for educational practice in the planning of mathematics instruction in higher education, specifically referring to the work of future teachers.

The behavioral approaches and learning processes under cognitive processes permeate the other three articles. Firstly, Poon et al. showed that children with ADHD, who are predominantly inattentive subtypes and have reading difficulties, exhibited diverse cognitive profiles. Poon et al. observed that students with reading difficulties were related to verbal and visual-spatial working memory deficits; however, ADHD students, predominantly the inattentive subtype, were associated with behavioral working memory deficits. Second, Zhao et al. studied the relationship between self-esteem and academic engagement in an adolescent sample, moderated by other variables: academic self- efficacy and perceived social support. The authors established that when students felt more social support, they increased their academic self-efficacy in their academic engagement. Based on the findings, the authors emphasize the importance of adolescent self-esteem, academic self-efficacy, and perceived social support as crucial factors within educational and familiar contexts. In the third, Alhossein talked about the teachers' knowledge and the use of evidence-based practices (EBPs) for students with autism spectrum disorder (ASD). The author showed that knowledge and use of EBPs were closely related. Also, he investigated two other predictors of teachers' use of EBPs for students with ASD, gender, and professional development programs. On the other hand, Alhossein indicated that teachers' knowledge of EBPs for students with ASD could be considered a vital indicator of teachers' use of EBPs. Applying these kinds of programs and practices would offer high-quality professional development programs through this research.

We can link these findings to the perspective of Macrine and Fugate about the importance of embodied cognition and learning. The authors analyzed and discussed their model, Translational Learning Sciences Research. They were convinced thoroughly of the importance of this model to improve new research methods in the cognitive, educational, and psychological fields while increasing the use of tools and new learning strategies in the classroom. Similar to Macrine and Fugate and Wang et al. analyzed a model of the effectiveness of online instructional tasks. They indicated the same effectiveness of the online program on lower-performing students and higher-performing students.

In summary, the contributions of neuroscience to the educational context are essential both for teachers to know what the most effective way is to educate and for students to take advantage of the instructional environment efficiently. In this sense, we need more future research to apply the significant advantages of modern brain recording and neuroimaging. On the other hand, the techniques in teaching-learning situations in academic educational contexts are accompanied by behavioral, pedagogical, and educational studies. They all explain what or how we should develop a teaching style that fosters meaningful learning in students, with the goal of forming more intelligent, conscious, and committed thinkers to solve the current challenges of our society.

## Author contributions

ML-R and EB wrote the manuscript. All authors contributed to the article and approved the submitted version.

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## Conflict of interest

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

## Publisher's note

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# Collaborative Learning Quality Classification Through Physiological Synchrony Recorded by Wearable Biosensors

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Interpersonal physiological synchrony has been consistently found during collaborative tasks. However, few studies have applied synchrony to predict collaborative learning quality in real classroom. To explore the relationship between interpersonal physiological synchrony and collaborative learning activities, this study collected electrodermal activity (EDA) and heart rate (HR) during naturalistic class sessions and compared the physiological synchrony between independent task and group discussion task. The students were recruited from a renowned university in China. Since each student learn differently and not everyone prefers collaborative learning, participants were sorted into collaboration and independent dyads based on their collaborative behaviors before data analysis. The result showed that, during group discussions, high collaboration pairs produced significantly higher synchrony than low collaboration dyads ($p$ = 0.010). Given the equivalent engagement level during independent and collaborative tasks, the difference of physiological synchrony between high and low collaboration dyads was triggered by collaboration quality. Building upon this result, the classification analysis was conducted, indicating that EDA synchrony can identify different levels of collaboration quality (AUC = 0.767 and $p$ = 0.015).

**Keywords: collaborative learning, physiological synchrony, electrodermal activity, heart rate, wearable biosensor, naturalistic class, ecological validity**



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## INTRODUCTION AND RELATED LITERATURES

In a world that is deeply connected, collaborative learning is believed to be the most important way of learning, shared knowledge construction, decision-making, critical thinking, and problem solving (Bruffee, 1999; Dillenbourg, 1999; Van Kleef et al., 2010; Gokhale, 2012). Scholars and practitioners advocating collaborative learning believe that learning is inherently active, constructive, and social. Successful collaboration benefits the whole group by immersing the students in an active learning condition to increase engagement and joint attention, relearn through retrieval, negotiate multiple perspectives, increase working memory resources, to name a few (Johnson and Johnson, 1985; Barron, 2003; Roediger III and Karpicke, 2006; Kirschner et al., 2009; Kuhn and Crowell, 2011). Broader education goals, such as involvement, cooperation and teamwork, and civic responsibility, are also believed to be achieved by collaborative learning (Smith and MacGregor, 1992).

Dillenbourg (1999) provided a general definition of collaborative learning as "a situation in which two or more people learn or attempt to learn something together." In this definition, "learn something" was broadly interpreted as activities, including "follow a course," "study course material," "perform learning activities such as problem solving," "learn from lifelong work practice," and "together," was interpreted as different forms of interaction. In fact, individual interaction is crucial in successful collaborative learning (Soller et al., 1998; Hiltz and Turoff, 2002; Kreijns et al., 2003), and thus serves as a key component of collaboration quality.

Given the importance of collaborative learning, the measurement of its quality is, however, very complex and challenging. Existing approaches can be categorized into subjective and objective measurements. Subjective measurement mainly relies on self-report data, including both interview (Salovaara and Järvelä, 2003; Sidani and Reese, 2018) and scales (Orchard et al., 2012; Organization for Economic Co-operation and Development (OECD), 2013); while objective measurement mainly relies on explicit observational data, which captures verbal communication and non-verbal behaviors (Odom and Ogawa, 1992; Marty and Carron, 2011; Mehl, 2017; Chi et al., 2018). The main defect of self-report data is the subject perspective that could be manipulated by the participants. For instance, the social desirability bias is a famous potential threat (Fisher, 1993; Holbrook and Krosnick, 2009).

Analyzing the verbal content of interactions is the most straightforward approach for analyzing the quality of interaction, in both face-to-face and computer supported contexts and has been commonly used in educational and psychological studies (Grau and Whitebread, 2012; Kent et al., 2016; Vuopala et al., 2016). The limitations of content analysis, include labor intensive and difficult, to provide instant feedback to either students or teachers. Thanks to the rapid development of computing capability and machine learning algorithm, non-verbal interactions, such as eye contacts, facial expression, and body movement, are also possible to be captured and analyzed (Montague et al., 2013; Tunçgenç and Cohen, 2018) and has been proved to be sufficient indicators of collaborative learning quality in face-to-face classroom or in online courses (Bronack, 2011; Al Tawil, 2019). These qualitative methodologies have shown rich effectiveness in the interpretation of human behaviors (Hsieh and Shannon, 2005; Elo and Kyngäs, 2008). However, there are still issues on trustworthiness of both the content analysis and the interpretation of explicit behaviors when using these methods alone (Elo et al., 2014). The implicit factors, such as emotional contagion, and affect infusion among individuals may be more crucial to cognition (Okon-Singer et al., 2015), but is far from being fully investigated due to challenges in measurement and data constraint (Fujiki et al., 2002).

As quite a few factors may affect the quality of collaboration, emotion is one of the most significant and moderates human behaviors in observable patterns (Balters and Steinert, 2017). Emotion regulation abilities are highly related to the success of interpersonal interactions, especially when the individuals collaborate with peers or in the workplace (Lopes et al., 2005; Eligio et al., 2012).

Educational activities require intensive interpersonal interactions. Thus, emotion plays an important role in education, especially in collaborative tasks (Schutz and Pekrun, 2007; Järvenoja and Järvelä, 2009). The effect can be either positive or negative (Imai, 2010). Comparing to verbal content, emotional state is directly detectable though quantitative measurements. Building upon the theory on human automatic nerves system (ANS), the important components of collaborative learning, such as cognitive load and emotional state, are believed to be monitorable through neurophysiological signals including EEG, fNIRs, ECG, and EDA. Arousal and valence can be evoked and detected in specific situations (Agrafioti et al., 2011; Boucsein, 2012; Ramirez and Vamvakousis, 2012; Dawson et al., 2017). The effects of individual interactions on emotion can also be measured through multimodal physiological signals (Heaphy and Dutton, 2008; Mønster et al., 2016).

Neurophysiological signals have been considered as promising measurements of emotional characteristics and can capture students' learning process that go beyond acquisition of knowledge (Léger et al., 2014; Ochoa and Worsley, 2016). Positive evidences on the correlation between interpersonal neurophysiological synchrony and interaction are consistently reported in recent years. Using various hyperscanning technologies, inter-brain synchrony has been identified during face-to-face communication or interactive decision-making (Jiang et al., 2012; Dikker et al., 2017; Hu et al., 2018), suggesting special neural processes recruited by interaction. Interpersonal physiological synchrony has also been consistently found during collaborative tasks and used as indicators of effective collaboration. Higher level of synchrony is associated with better task performance and learning gains in collaborative tasks (Ahonen et al., 2016; Pijeira-Díaz et al., 2016; Dich et al., 2018).

However, brain hyperscanning devices are usually not easily to use in real classroom learning, because of people's concern on health safety issues of brain hyperscanning, and their visual interruption to both students and teachers. Data quality might also be a problem in naturalistic settings (Matusz et al., 2019). Physiological signal, on the other hand, can be easily and steadily recorded at distal sites, such as fingers and wrists (Boucsein, 2012), and thus easily accepted by parents and students. The majority of existing studies that measure physiological synchrony in collaborative learning are basically lab-based experiments (Pijeira-Díaz et al., 2016; Dich et al., 2018; Dindar et al., 2019). The tasks include open-ending problem-based learning topics, such as designing breakfast for marathoners, (Haataja et al., 2018) or pair-programing task with restricted solutions (Xie et al., 2018). Although a few of them collected data in real classroom (Ahonen et al., 2018), they only reported correlation between synchrony and collaboration, but did not further explore the practical potential of categorizing collaboration quality through synchrony in naturalistic scenarios.

Naturalistic scenario, instead of laboratory setting, is crucial in the research of collaborative learning. First, it is social in nature and cannot be simulated in fully controlled, isolated environment. Second, it is constructive and targets at high-level cognitive skills, such as problem-solving, knowledge construction, and collaboration, and cannot be substituted by simple cognitive tasks, which are frequently used in laboratory investigations. Third, even applying ethologically relevant stimuli in a laboratory context, participants may react differently in both behaviors and neurocognitive signals (de Heer et al., 2017; Qu et al., 2020). In the real classroom context, the interaction behavior varies across students, which is very different from laboratory settings, where participants will try their best to comply to the research design. In fact, naturalistic real-world research is believed to be necessary to understanding human behaviors in neuroscience (Matusz et al., 2019). Classroom learning can serve as an ideal semi-structured scenario to bridge the laboratory based research and the real world.

The rapid development of wearable biosensing technologies makes it possible to record neurophysiological signals during naturalistic classroom learning. Recently, researchers used portable EDA and EEG sensors in classroom to record the neurophysiological signals of teachers and students in variance of learning conditions including lectures, discussion, movie viewing, and real exam (Dikker et al., 2017; Poulsen et al., 2017; Zhang et al., 2018; Qu et al., 2020). By recording physiological signal in fully real-world collaborative learning, the present study attempts to apply physiological synchrony to predict interaction quality in real collaborative learning. Although collaborative activities can range from classroom discussions to team research that covers a whole semester or year, this study focuses on classroom discussion as it is the simplest and most general scenario among diverse collaborative learning approaches.

In the current study, the researchers collected physiological and behavioral data from naturalistic class sessions and analyzed interpersonal synchrony during individual and collaborative tasks. Students were naturally divided into two kinds of collaborative dyads (CDs) according to their different learning styles as captured by behaviors, i.e., CDs and IDs. The result showed a significant difference in interpersonal physiological synchrony between CDs and IDs, i.e., high and low interactive levels. Following classification analysis confirmed the potential of applying physiological synchrony as an indicator of collaboration quality. This finding is promising in future applications of evaluation in student learning style.

# MATERIALS AND METHODS

## Participants

Participants were recruited from an undergraduate level elective course that requires no prerequisite domain knowledge. All participants were Chinese nationals and full-time university students. The 16 students who registered in this course were from 12 different departments and programs across natural sciences, pharmaceutical science, engineering, social sciences, and humanities. Data collection lasted for two class sessions in 2 consecutive weeks. Fifteen out of 16 students ($M$ = 21.61, SD = 2.43, eight females) signed the informed consent form at the beginning of the first data collection session. One student quit at the second session due to health conditions.

Sixteen students formed four three-people and one four-people discussion groups at the beginning of the semester, resulted in 16 dyads in the first data collection session. The grouping was simply decided by their seat location and most of them were strangers to each other at the before taking this course. In the second session, the grouping remained the same. There were 14 dyads since one person quit from a three-people group, making a total of 30 dyads. Dyad no. 15 was eliminated from all analyses and no. 13 and no. 15 were eliminated from analyses on collaborative learning, because one student in this group shared laptop screen with their teammate and discussed (pair no. 15) during the independent task (IT), violating the experiment requirement (**Figure 1**).

## Experimental Tasks and Materials

Each course sessions had two main parts. In the second half of each class session, after the lecture, the instructor assigned an open-ended problem to the class. Students were required to solve the problem independently first (IT), followed immediately by a group collaborative discussion (interaction analyzed in pairs, PT) on the same problem. The problems in both steps were the same, except that participants were asked to solve the problem alone or with group members. In the first class session, the students were asked to review course materials and sort out a list of key knowledge by its significance, then discuss with their group members to forge a comprehensive agreement on the list. In the second class session, the students were asked to explore new approaches for engagement measurements alone and then discuss with their group members to form a comprehensive approach. The group would share their final solution to the whole class.

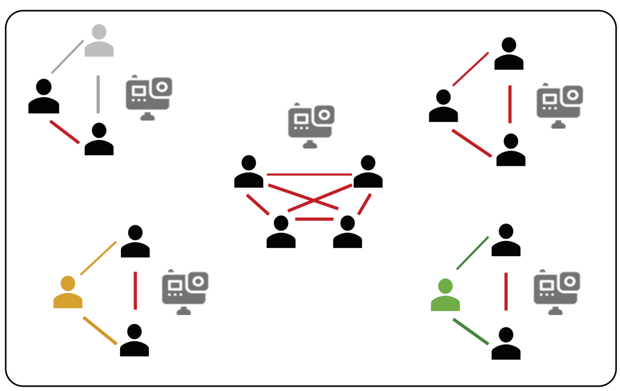

**FIGURE 1** | Classroom setting and intra-group dyads. The gray figure did not participate in the study at all. The yellow figure and nodes were excluded from the first data collection session because of the violation of experiment requirement. The green figure quit the study in the second-round data collection session because of health conditions. Thus, a total of 28 dyads were used in the analyses.

A short survey was used to evaluate participants' engagement level and emotional state during IT and PT, respectively. The engagement level was self-reported by the participants with a 5-point Likert scale. The emotional state was measured with a five-scale Self-Assessment Manikin (SAM) to rate the affective dimensions of valence, arousal, and dominance (Bradley and Lang, 1994).

### Settings and Apparatus

The settings followed the naturalistic class settings of this course. Each student had their own chair desk with rolling wheels. Skin conductance and heart rate (HR) was collected from each participant using the unobtrusive Huixin Psychorus wristband (Beijing Huixin Technology, 2021), capturing data at a sampling rate of 40 Hz for EDA and 1 Hz for HR. Each group was videotaped during both IT and collaborative discussion.

### Procedures

Before the beginning of the first data collection session, researchers collected the signed informed consent and helped the students to wear the wristbands properly to ensure good data quality.

There was a 3-min close-eye baseline session and a 2-min open-eye baseline session before the IT. After the baseline sessions, all instructions were given by the instructor. The independent step last for 7–10 min and the group collaborative learning task last for 12–17 min. The short survey was collected immediately after IT and PT (**Figure 2**). Two to five minutes were cut from the beginning of the PT sessions to eliminate any continued effect from the IT sessions in data analysis. Students' own physiological data reports were provided to them after the data collection to appreciate their participation.

### Physiological Data Preprocessing

Skin conductance was collected using galvanic skin response (GSR). GSR records the changes of the electrical activity on the skin. The more general name of the GSR is electrodermal activity also known as EDA (Boucsein et al., 2012). The term EDA will be used to refer to the skin conductance signal in the following part of the article. The visual inspection was performed to control the quality of the raw EDA signals. Samples of the EDA signal clips during independent and paired tasks were randomly selected for visual inspection and artifacts manual removal. The cleaned data were used for further calculations. The results of the new dataset were then compared with the results from the original data set. Since the difference between two datasets was not significant, manual artifacts removal was skipped for the whole sample to minimize the influence on the raw data. The signals were then smoothed using the Gaussian smoothing algorithm and was down sampled from 40 to 10 Hz in a MATLAB-based EDA analysis software (Ledalab 3.4.9; Benedek and Kaernbach, 2010).[1]

## Analysis and Results

### Ground Truth and Procedure of Analysis

In naturalistic setting without artificial design, ground truth should first be defined before physiological data analysis. The ground truth is that students learn differently and not everyone prefers/suites collaborative learning. In the real class sessions, students acted in their own learning style, which refers to the stable trait which decides how learners perceive and respond to learning environments (Keefe, 1979). The Felder and Silverman mode categorizes students' learning style into five dimensions: active/reflective; sensing/intuitive; visual/verbal; sequential/global; and inductive/deductive (Felder and Silverman, 1988; Alfonseca et al., 2006). Active learners prefer to internalize information from external environments, and they are more likely to share opinions with peers frequently during collaboration; however, reflective learners tend to examine and process information by themselves (Felder and Silverman, 1988). That is, even though the students were equally engaged in the tasks, they may generate different perspectives and preferences for collaborative learning mode, and use different cognitive strategies during interaction (Cabrera et al., 1998; Kayes, 2005). The homogeneity of learning styles within a group will also affect the interactive effect, and the higher homogeneity group members may have better collaboration quality (Alfonseca et al., 2006).

Thus, participants were sorted into CDs and IDs based on their collaborative behaviors. **Table 1** presents the collaboration events and their descriptions. CDs are expected to have higher quality interaction during collaborative task and generate higher physiological synchrony.

A series of hypothesis test were conducted to compare groups of participants along different dimensions. The tests were performed by $t$-test. Before performing the $t$-tests, tests of normality (Kolmogorov-Smirnov and Shapiro-Wilk) were applied to the EDA synchrony, engagement, and emotional state datasets for IT and PT, all the tests did not show significant departure from normality. Therefore, the EDA synchrony, engagement, and emotional state variables for IT and PT were normally distributed. Classification analysis was then applied to see if physiological synchrony can identify collaborative learning quality. **Figure 3** indicates the logic of the whole analysis.

[1]www.ledalab.de


**FIGURE 2** | Procedure of the class data collection.

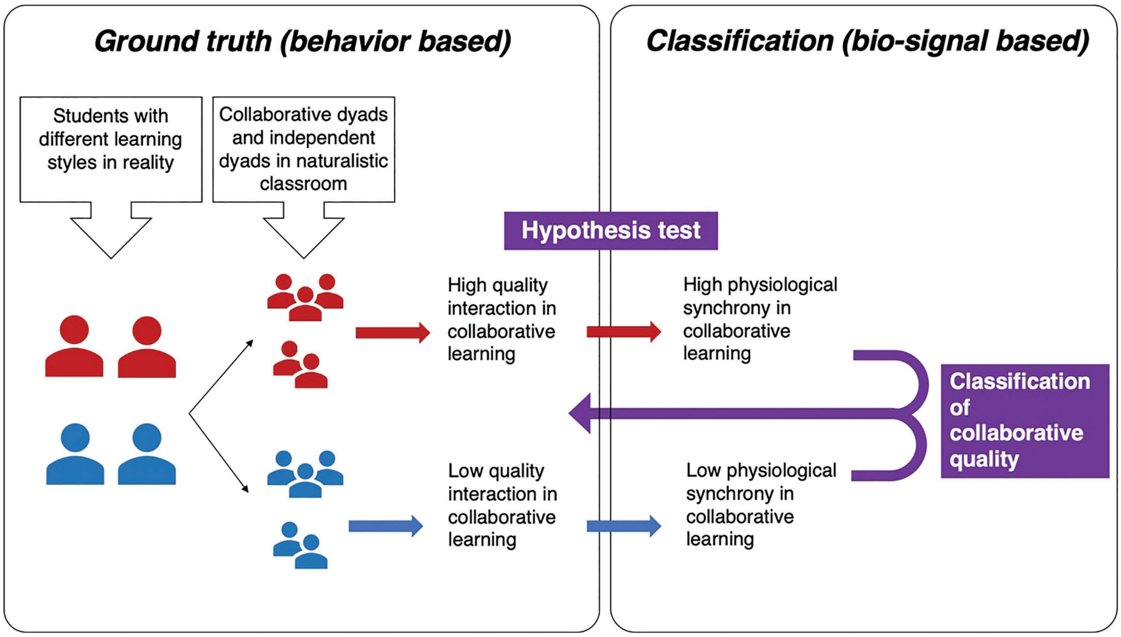


**FIGURE 3** | Participants were categorized into collaborative dyads (in red) and independent dyads (in blue) according to the behavioral indicators during collaborative learning task. A hypothesis test was performed to explore the relationship between collaboration behavior and physiological synchrony during collaborative learning. At last, the classification analysis was applied to test the effectiveness of physiological synchrony as an identifier of collaborative learning quality.

## Define Collaborative and Independent Dyads

In the current study, two raters watched the videos of the group discussion and categorized the dyads into high or low collaboration style without being aware of the physiological data analysis. Effective interaction includes verbal and non-verbal interactions such as tight conversation, eye contact, and joint attention on course material. As discussed in the previous section, better collaboration behavior quality is strongly correlated with collaborative learning quality including mutual gaze and joint attention (Schneider and Pea, 2013).

The two raters recorded the time range of key interaction events in the video for each pair of students. For groups with three people, when the total time of interaction events exceeds 1/3 of the total time of PT, this pair is then categorized to CDs, otherwise to IDs. For the one group with four people, the threshold is set to 1/6 since there are six different pairs of students sharing the total interaction time. Fifteen dyads were sorted to CD and 14 dyads to ID.

**TABLE 1** | Collaboration events and descriptions.

| Collaboration events | Description |
|---|---|
| Tight conversation | Discussion on one focused point between two people for several rounds |
| Eye contact | Though not talking, the person communicates with their teammates by eye contact, expressing agreement and disagreement on the topic |
| Joint attention | Two people show joint attention on the third object such as course material, laptop screen, or the blackboard in the front of the classroom. |

## Engagement and Emotional Statement

It is important to check the validity of experimental settings in naturalistic classroom. First, students' engagement levels should be the same across the two sessions to ensure that any identified differences are not due to engagement differences. Second, students' self-report on their subjective experience during IT and PT should be compared to check if the IT and PT did mean different learning strategies to them.

According to **Figure 4**, engagement difference was not found between IT and PT. The participants were equally and highly engaged in both the IT ($M$ = 2.76, $SD$ = 0.951) and group discussion task (PT, $M$ = 3.00, $SD$ = 1.035), $t(28) = 1.565$, $p = 0.258$. This result suggests that participants were equally and highly engaged in both IT and PT, making engagement less likely to be the possible confounding factor for the additional synchrony during collaboration.

Same analysis was also conducted on the three affective dimensions. During group discussions, participants were more aroused (PT: $M$ = 2.03, $SD$ = 0.944; IT: $M$ = 1.14, $SD$ = 0.833, $t(28) = 3.455$, $p = 0.002$) and experienced higher positive emotion (PT: $M$ = 2.93, $SD$ = 0.813; IT: $M$ = 2.11, $SD$ = 0.875, $t(27) = 5.037$, $p < 0.001$). In the independent sessions, the participants reported to be more in control to their situation (PT: $M$ = 1.90, $SD$ = 0.673; IT: $M$ = 2.79, $SD$ = 1.013, $t(28) = -5.363$, $p < 0.001$). Higher score on arousal and valence indicated pleasant and excited discussion atmosphere during the collaborative learning

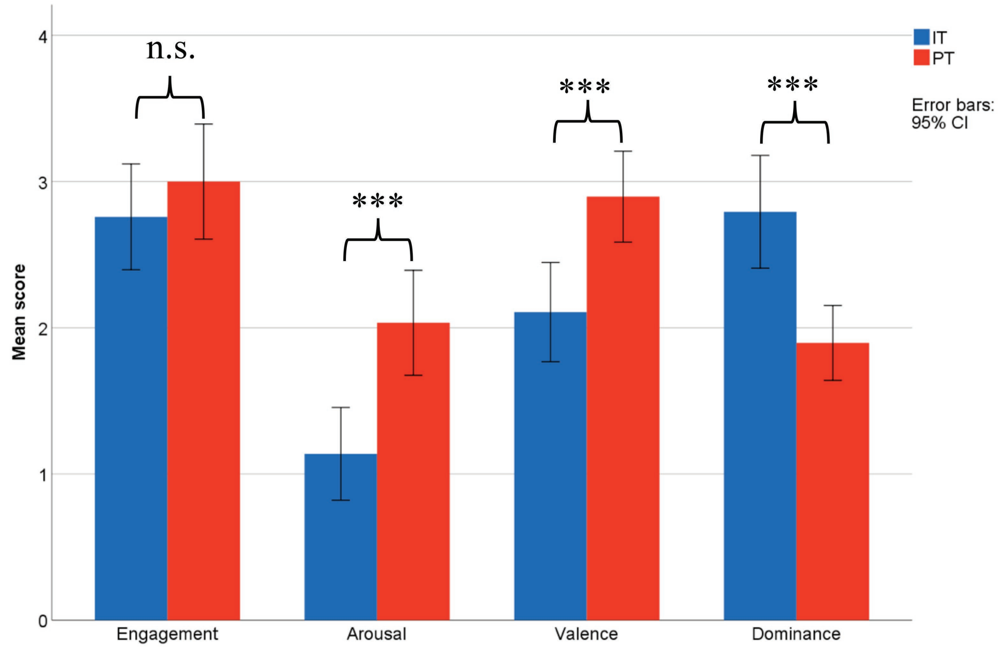


**FIGURE 4** | Engagement and emotional state between IT and PT. ***$p < 0.001$.

task. Lower score in dominance is reasonable during PT since the process of multi-personal discussion came with negotiation and compromise (**Figure 4**).

## Physiological Synchrony

The algorithm for the computation of EDA synchrony was adopted from Marci and Orr (2006) and calculated the moment-by-moment physiological concordance named as single session index (SSI). Same algorithm was also implemented on HR.

It should be noted that the EDA signal used in the analysis was the overall EDA instead of plain skin conductance level (SCL) or skin conductance responses (SCRs). The SCL represents the tonic level of electrical conductivity of the skin, relating to the slow and background change of EDA. The SCRs represent the phasic changes of electrical conductivity of the skin, reflecting the rapid and event-related changes of EDA (Braithwaite et al., 2013; Posada-Quintero and Chon, 2020). This study did not focus on the SCRs of the physiological signal and paid more attention on the overall changing trend of the EDA. But to keep the high ecological validity of this naturalistic experiment, the researchers chose to not eliminate the possible influence of SCRs for the authenticity of the study.

First, the 10 Hz signal was further down sampled by averaging the 10 numbers in each second. The moment-by-moment slope of the 1 Hz data for each signal was then calculated using a 5-s window with a regression model at a 1-s roll-rate. Next, Pearson correlations were conducted on the slope for each pair of data with a 15 s window rolling at the rate of 1 s, reflecting a moment-by-moment synchrony in the last 15 s. The SSI is an index that shows the synchrony over a time period instead of discrete time points. It is the natural logarithm of the ratio of the sum of positive correlation coefficients divided by the absolute value of the sum of negative correlation coefficients over a given period of time.

$$\mathrm{SSI} = \ln \frac{\sum_{i=0}^{n}(r_i|r > 0)}{\left|\sum_{i=0}^{n}(r_i|r < 0)\right|}$$

A sample of each step of the signal processing and synchronization calculation for IT and PT is shown in **Figure 5**.

In the EDA-IT figure, (a) is the raw EDA signals of pair no. 10 in IT; (b) is the trajectory of slope for a 5-s window, rolling on the rate of 1 s; and (c) shows the moment-by-moment correlation coefficients on a 15-s window. The three panels are the same as in the EDA-PT figure. This is an example of the same pair in the collaborative task. The synchrony (SSI) was higher than that of in IT. The figures in the third and fourth row are examples of HR data.

It is interesting to find that synchrony on EDA during IT and PT reflects different styles of learners. When doing the IT, the synchrony level between ID ($M$ = 0.322, $SD$ = 0.449) and their CD peers ($M$ = 0.009, $SD$ = 0.485) was not significant [$t(27)$ = 1.800, $p$ = 0.084]; while during the group discussion, the synchrony among ID ($M$ = −0.170, $SD$ = 0.396) was significantly lower than the CD ($M$ = 0.231, $SD$ = 0.380), $t(27)$ = 2.781, $p$ = 0.010 (**Figure 6**).

The results showed in **Figure 6** also showed that SSI was significantly lower for ID during PT, as compared to IT [$t(27)$ = 3.070, $p$ = 0.005].

Same analysis was conducted to explore the difference of synchrony of HR. When doing IT, ID ($M$ = 0.171, $SD$ = 0.462)

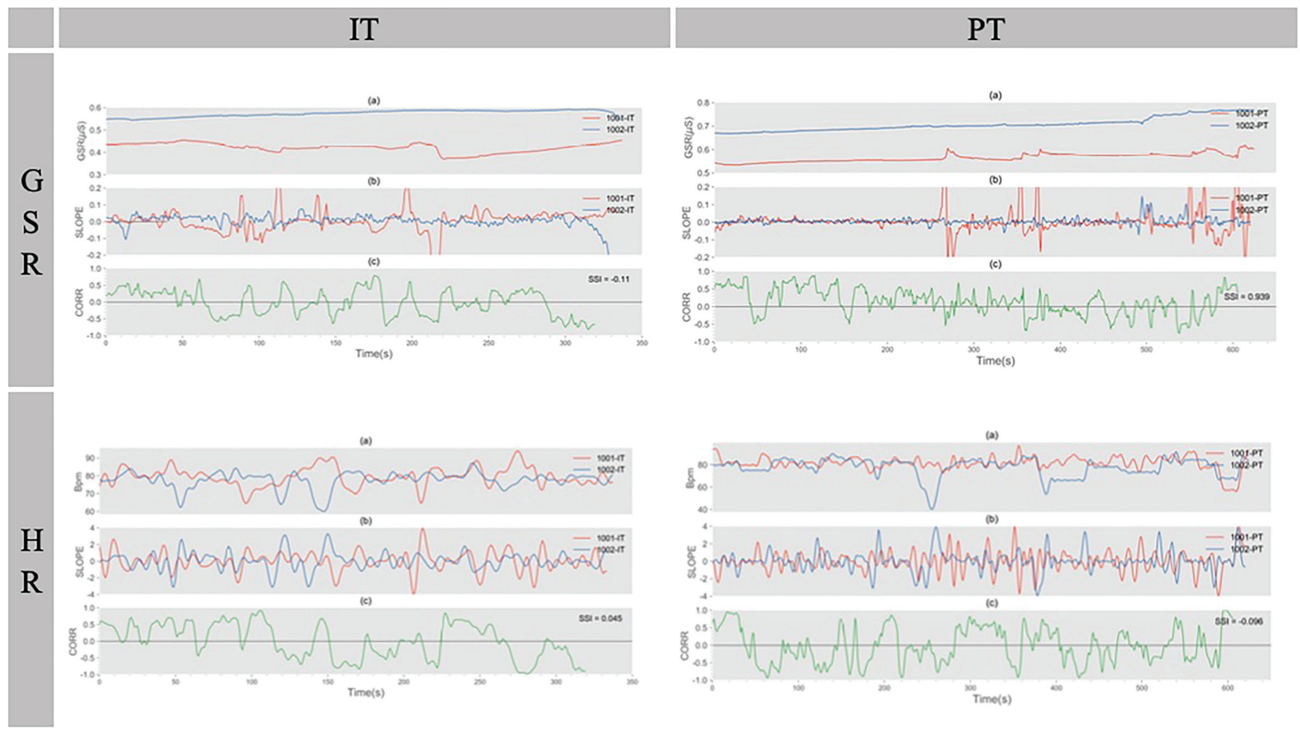


**FIGURE 5 |** A sample of electrodermal activity (EDA) and heart rate (HR) data processing in the EDA-IT figure, (a) is the raw EDA signals of pair No. 10 in IT; (b) is the trajectory of slope for a 5-second window, rolling on the rate of 1 second; (c) shows the moment-by-moment correlation coefficients on a 15-second window. The three panels are the same as in the EDA-PT figure. This is an example of the same pair in the collaborative task. The synchrony (SSI) was higher than that of in IT. The figures in the third and fourth row are examples of HR data.

and CD ($M$ = −0.158, $SD$ = 0.637) showed insignificant difference, $t(26) = 1.157$, $p = 0.129$; and during PT, there was also no significant difference between the synchrony among ID ($M$ = −0.076, $SD$ = 0.446) and the CD ($M$ = −0.106, $SD$ = 0.327), $t(26) = 0.203$, $p = 0.841$ (**Figure 7**).

### Physiological Synchrony as a Classifier of Collaborative Learning Quality

Since there is a strong correlation between the interaction level and EDA synchrony, a receiver operating characteristic (ROC) analysis was performed to test the accuracy of synchrony as a classifier of the collaborative learning behaviors in both IT and PT. Results showed that SSI is an acceptable indicator to identify interaction levels for collaborative task (AUC = 0.767, $p = 0.015$). Synchrony did not discriminate different collaboration styles during IT (AUC = 0.343, $p = 0.15$), which is good since there was no collaborative behaviors and no significant difference between CD and ID during IT. The results of IT and PT together verified the robustness of synchrony as the predictor for collaborative learning quality (see **Figure 8**).

Same analysis was also applied on HR data. As shown in **Figure 9**, the synchrony of HR exhibited low accuracy in classifying collaboration style (AUC = 0.454, $p = 0.679$) during PT. This is consistent with the low HR synchrony and undifferentiated HR synchronization level across collaborative learning quality.

## CONCLUSION AND DISCUSSION

The aim of the present study is to explore the potentials of using physiological synchrony to classify collaboration quality in realistic educational settings, based on consistently identified synchrony during interpersonal interaction by previous studies. Existing studies show that learners are diverse in learning style and collaborative learning can manifest this diversity while students take different roles in the learning process (Smith and MacGregor, 1992; Pashler et al., 2008).

In the current study, the participants were categorized into CDs and IDs according to their natural behaviors in the collaborative learning tasks, and this behavioral difference significantly correlated with EDA synchrony between the pairs of participants. The results showed that participants who were categorized as CD during group discussions were associated with higher EDA synchrony. However, there was no significant difference between CD and ID in collaborative tasks in their HR synchrony.

One possible explanation for these inconsistent results in EDA and HR may have to do with the fact that talking affects one's cardiovascular system but not EDA. Talking, even without emotional expression, can increase the blood pressure of hypertension patients (Le Pailleur et al., 2001). Simple mental and verbal activities also affect HR variation through changes in respiratory frequency (Bernardi et al., 2000). On the other

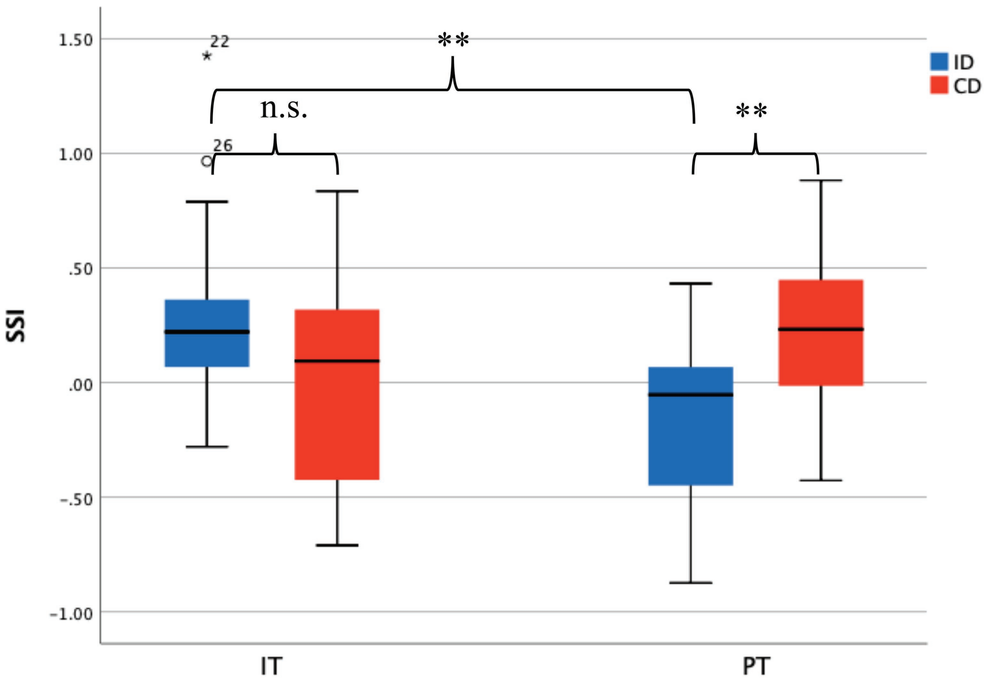


**FIGURE 6 |** Single session index (SSI) among CD is significantly higher than that in ID during collaborative learning tasks. $^{**}p < 0.01$.

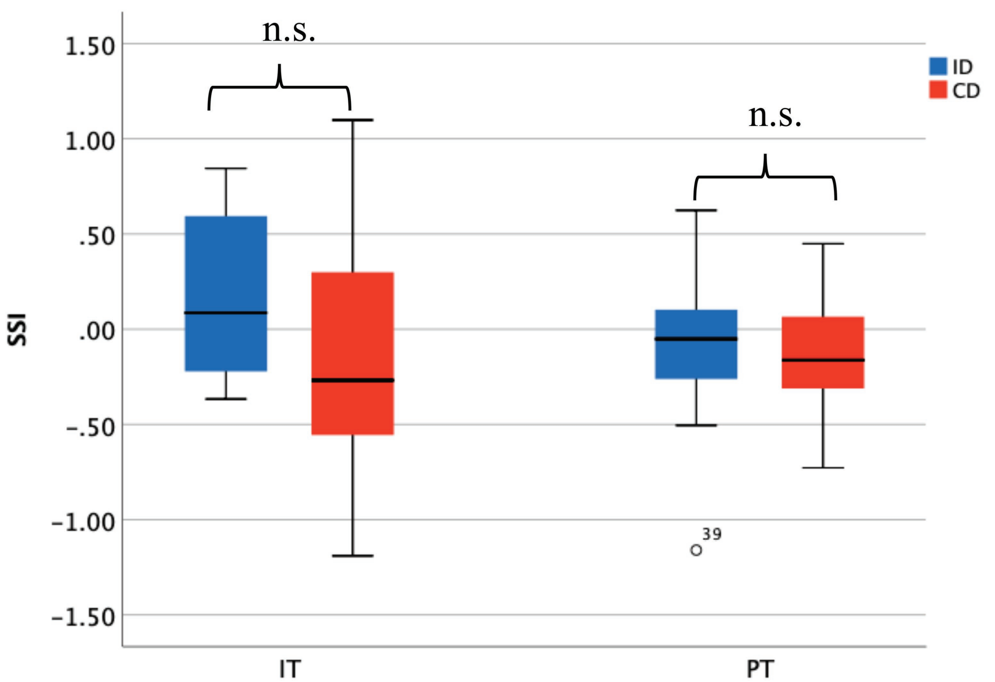


**FIGURE 7 |** HR synchronization did not show significant difference between ID and CD during IT and PT.

hand, no evidence was found for the correlation between EDA and free talking (Fowles et al., 2000). In the natural group discussion context, students focused on the same task, trying to forge an integrated answer. Among CD, two students were tuning their emotional state during the discussion, resulted in higher synchrony in EDA. But when two people talk, they talk

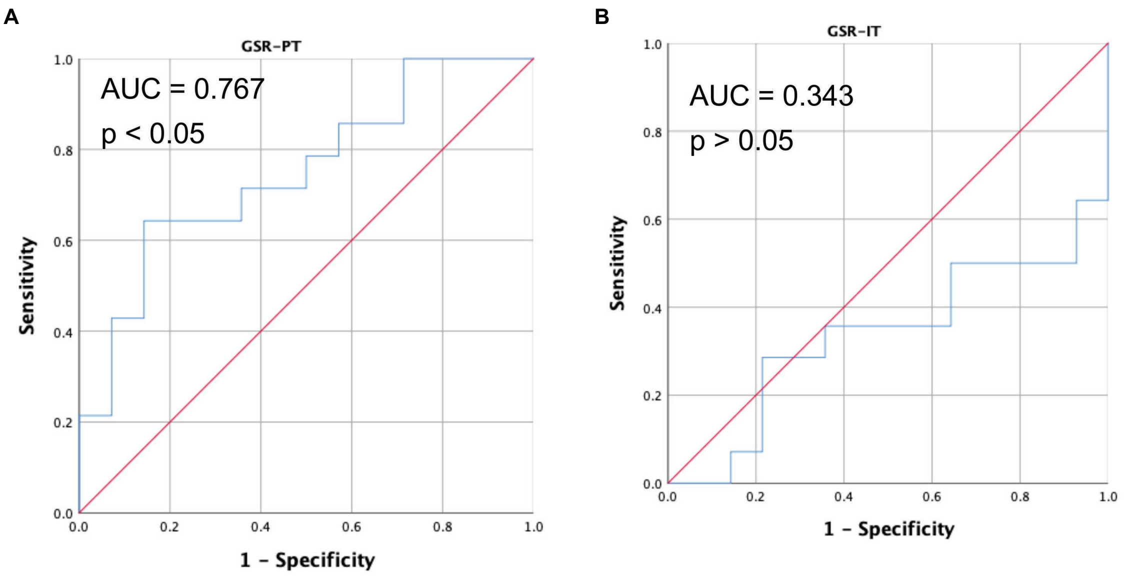


**FIGURE 8 |** The ROC curve of EDA for PT **(A)** and IT **(B)** using synchrony as classifier for collaborative learning quality.

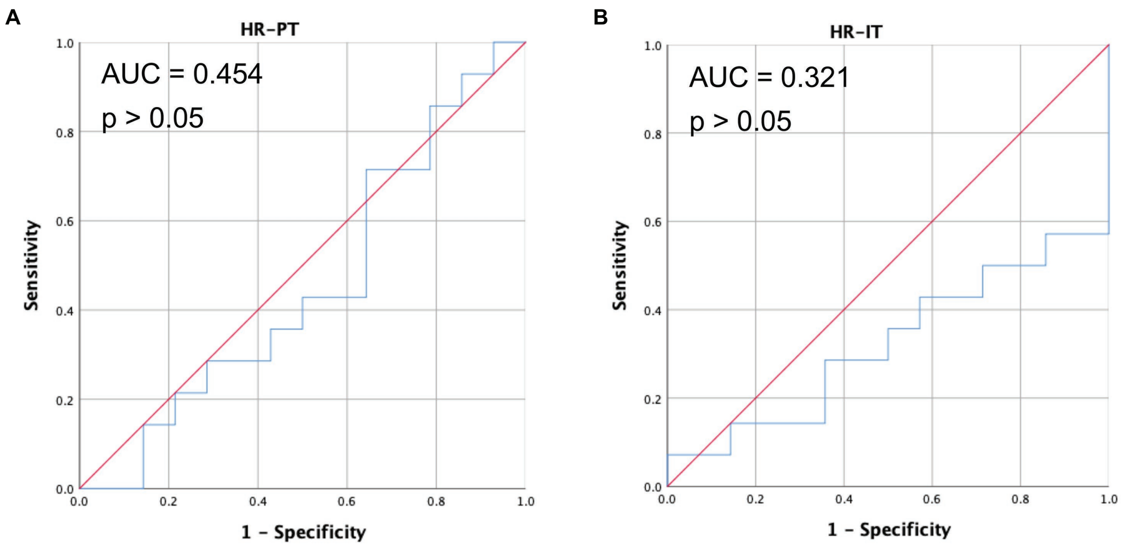


**FIGURE 9 |** The receiver operating characteristic (ROC) curve of HR for PT **(A)** and IT **(B)** using synchrony as predictor for collaborative learning quality.

in turns, not simultaneously, thus the asynchronous HR. Actually, when participants doing verbal and motor activities in unison, HR synchrony was significantly higher than during unsynchronized moments (Müller and Lindenberger, 2011; Noy et al., 2015). Therefore, even the cognitive and emotional elements that generated synchrony in EDA may also synchronize HR in cognitive tasks as reported in the laboratory based studies (Henning and Korbelak, 2005; Montague et al., 2014; Mitkidis et al., 2015), the effect could be mixed with that of talking on one's HR. While on the other hand, EDA synchrony was identified during unstructured conversation (Silver and Parente, 2004).

The result also showed that during PT, the EDA synchrony of ID was significantly lower when during IT. It seemed counterfactual on first thought but it could be reasonable if learning style was brought into consideration. Learners differ in the preference for collaborative learning (Cabrera et al., 1998). As a result, different people would choose different learning strategies. Independent learners may prefer to learn by themselves and process information in a more implicit way. When doing IT, this kind of learners can spend more cognitive resources on their task, thus two learners may show a moderate physiological synchrony as shown in **Figure 6**. But when they were in collaborative learning context, they have to spare part of their cognitive resources to other people or the entire environment, or could be overwhelmed by the intense communication in the group. In this case, the ID participants may show an even lower physiological synchrony than during IT.

Classification analysis proved that physiological synchrony may serve as a good indicator for interpersonal interaction quality. Higher physiological synchrony is positively correlated with higher interaction level. That is, higher frequency and longer time of interaction behaviors. Similar approach can be found in the research of predicting communication behavior using neural or physiological synchronization (Henning et al., 2009; Jiang et al., 2012). This application can help to identify different collaborative learning quality of the learners. It can also give instructors feedback on course content. One student may be attracted to one topic or interaction scheme but disinclined to another. In such case, physiological synchrony can provide clues in teaching adjustment.

Our findings provide evidence for the potential application of biosensors in the real-world classroom. We focus on the connection between the bio-signals and human behaviors on which we believe is the advantage of this interdisciplinary research area. This project also suggests that future researches in the same realm place attention to the scope of appropriate assumptions and research questions so that the laboratory-based experiments and naturalistic setting studies can be good complement for each other.

Students' immediate learning outcome was not evaluated as the tasks were open-ended class discussions. Next, we will choose class sessions that has planned quizzes as a measure of learning 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 Institute of Education, Tsinghua University. The patients/participants provided their written informed consent to participate in this study.

## AUTHOR CONTRIBUTIONS

YL, TW, and YZ designed the experiments and drafted the manuscript. YL, TW, and KW carried out the fieldwork and collected and analyzed the data. All authors contributed to the article and approved the submitted version.

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# Self-Esteem and Academic Engagement Among Adolescents: A Moderated Mediation Model

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As an important predictor of academic achievement and an effective indicator of learning quality, academic engagement has attracted the attention of researchers. The present study explores the relationship among adolescent self-esteem and academic engagement, the mediating effect of academic self-efficacy, and the moderating effect of perceived social support. Four-hundred and eighty adolescents ($M_{age}$ = 14.92) from the Hebei Province of China were recruited to complete anonymous questionnaires. The results show that self-esteem positively predicted adolescent academic engagement through the indirect mediating role of academic self-efficacy, and the percentage of this mediation effect of the total effect was 73.91%. As a second-stage moderator, perceived social support moderated the mediating effect of academic self-efficacy. Specifically, when students felt more perceived social support, the impact of academic self-efficacy on their academic engagement was greater. Our findings suggest that adolescent self-esteem, academic self-efficacy, and perceived social support are key factors that should be considered together to improve adolescent academic engagement. Therefore, parents and school educators should actively guide adolescents to improve their self-esteem and academic self-efficacy. Parents and educators should also construct an effective social support system to improve students' perceived social support and enhance their academic engagement.

**Keywords: academic engagement, academic self-efficacy, adolescents, perceived social support, self-esteem**

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## INTRODUCTION

With the development of positive psychology, human strengths and positive psychological qualities have received widespread attention. Researchers have focused on the positive opposite of burnout – "engagement" – which is defined as a positive, fulfilling, work-related state of mind, characterized by vigor, dedication, and absorption (Schaufeli and Bakker, 2004). Academic engagement extends the concept of engagement, and it refers to the degree to which students engage in educational learning tasks (such as school-related coursework and learning activities) in the process of formal education (George, 2009). Existing literature suggests that high academic engagement promotes academic achievement (Johnson and Sinatra, 2013), improves physical and mental health (Wefald and Downey, 2009), enhances students' school adjustment ability (Wang and Fredricks, 2014), and reduces students' dropout decisions (Fan and Williams, 2010). On the contrary, low academic engagement among adolescents can lead to academic failure, dropping out of school, drug abuse, juvenile crime, and the increase of negative emotions such as anxiety and depression (Leslie et al., 2010; Li and Lerner, 2011).

Adolescence is a sensitive and critical period of development (Blackwell et al., 2007), during which adolescents bear heavy schoolwork pressure while also adapting to significant physical and psychological changes. Some adolescents often experience recurring negative emotions such as anxiety and depression (Sahin, 2014). In the Chinese education system, the phenomenon of examination-oriented education is serious. The standard of educational evaluation is single which takes score as only standard and much utilitarian awareness on violating nature of education exists in current education (Wang, 2004). Adolescents' academic performance is regarded as a critical indicator of their ability to learn (Christenson et al., 2012). Researchers have explored the psychological factors (other than classroom teaching and learning methods) that affect academic performance, and this scholarship has concluded that academic engagement can effectively predict students' current academic performance (Hershberger and Jones, 2018) and also influence their future functional growth (Fredricks et al., 2016).

However, we reviewed the relevant literature and found that the research on academic engagement has focused generally on college students. Specifically, it has focused on the characteristics of the class environment, such as the teacher-student relationship (Yang and Lamb, 2014) and peer relationships (Fredricks et al., 2004), and the characteristics of the family environment, such as family socioeconomic status (Randolph et al., 2006) and family support (Blondal and Adalbjarnardottir, 2014). There has been little research focus on the relationship between individual characteristics and academic engagement (Li and Li, 2021). Self-esteem and self-efficacy have been confirmed to have an impact on academic engagement, but there is no research to confirm the respective contributions of these two factors, or on their combined impact on academic engagement. Moreover, research on the regulating mechanism of academic engagement is sparse. Therefore, it is necessary to explore the influence of the psychological factors that regulate or intervene in the academic engagement of adolescents; to fully consider the supportive resources of family, school, and society; and to put forward a plan to improve adolescent academic engagement that helps adolescents navigate the sensitive and critical period of adolescence more smoothly.

## Self-Esteem and Academic Engagement

Self-esteem is the evaluation of an individual's beliefs and attitudes toward his or her abilities and values (Rosenberg, 1965). Self-esteem during adolescence tends to be unstable, because of the many changes that occur in the adolescents' roles and responsibilities. Self-esteem tends to decline in early adolescence and recover in the middle and later stages of adolescence (Trzesniewski et al., 2003). Adolescents with high levels of self-esteem tend to experience positive self-experiences (Peng et al., 2019), high-quality interpersonal relationships (Cameron and Granger, 2019), and better physical and mental health (Li et al., 2010).

As a basic psychological structure, self-esteem can serve as a motivator for academic engagement (Lim and Lee, 2017). Expectancy-value theory suggests that individuals' positive self-evaluation can predict academic outcomes, such as academic engagement (Fang, 2016). A study by Sirin and Rogers-Sirin (2015) showed that self-esteem affected the fields related to academic engagement, and that there was a significant positive correlation between self-esteem and academic engagement. The research data of Filippello et al. (2019) found that self-esteem can predict a person's level of academic engagement. Thus, we propose the following hypothesis:

> *H1*: *Self-esteem positively predicts adolescent academic engagement.*

## Academic Self-Efficacy, Self-Esteem, and Academic Engagement

Another term related to academic engagement that has also attracted widespread research attention is academic self-efficacy. Schunk (2003) defined this term as a student's judgment of his or her ability to complete an academic task. Alivernini and Lucidi (2011) posited that academic self-efficacy reflected students' cognitive ability in their academic fields and predicted academic achievement. Many studies have shown that academic self-efficacy has an impact on students' academic engagement (Uçar and Sungur, 2017; Liu et al., 2020). On the one hand, academic self-efficacy affects students' academic efforts and persistence. Compared with students with low levels of academic self-efficacy, students with high levels of academic self-efficacy commit to higher goals and academic expectations, have stronger resistance to frustration, and demonstrate greater persistence when facing difficulties (Wright et al., 2012). On the other hand, students' confidence in their academic ability can influence their participation in school activities and learning tasks (Eccles and Wigfield, 2002). Students who are confident in their academic abilities will put more effort into academic tasks, while those who lack self-confidence will be less engaged in their studies and are more likely to give up.

As mentioned in section "Self-Esteem and Academic Engagement," self-esteem has a significant impact on academic engagement. However, it remains to be further explored how self-esteem influences academic engagement and what internal mechanism drives this relationship. Self-efficacy theory posits that academic self-efficacy is a motivational factor that can induce and maintain adaptive learning behaviors (Ruzek et al., 2016). Whether self-esteem can affect adolescents' academic engagement through academic self-efficacy is worthy of in-depth discussion.

Self-esteem and self-efficacy are connected but different concepts (Judge and Bono, 2001). Self-esteem is a positive evaluation of one's value and importance; that is, an individual's evaluation of "being a person." Self-efficacy is the speculation and judgment about whether a person can complete a certain task, and it is the evaluation of the individual's ability to "do things," based on experiences in specific activities. Previous literature has shown a significant positive correlation between self-esteem and academic self-efficacy (Batool et al., 2017). Students with positive self-esteem have higher levels of academic self-efficacy (Pahlavani et al., 2015). Both self-esteem and academic self-efficacy affect individual academic engagement, and self-esteem is closely related to academic self-efficacy; therefore, we can reasonably assume that academic self-efficacy is likely to play a mediating role between self-esteem and academic engagement. Thus, we hypothesize the following:

*H2*: *Academic self-efficacy mediates the association between self-esteem and adolescent academic engagement.*

## Perceived Social Support, Academic Self-Efficacy, and Academic Engagement

Although self-esteem may affect adolescents' academic engagement through academic self-efficacy, this effect varies from person to person. Perceived social support refers to the individual's feelings and evaluation of the degree of support he or she receives from family, friends, and important others (Zimet et al., 1988). Social learning theory (Bandura, 1977) suggests that others' guidance, expectations, and support will affect an individual's self-efficacy. Academic engagement plays an important role in individual development, but it is malleable and does not always occur autonomously. When individuals perceive high levels of external support and expectations, their positive learning motivation can be stimulated (Gettens et al., 2018), and the strength of this learning motivation has an important impact on students' academic engagement (Liu et al., 2009).

However, the existing literature lacks the exploration of the mechanism of the impact of perceived social support on academic self-efficacy. Existing studies have shown that perceived social support can regulate the relationship between self-efficacy and learning goals (Bagci, 2016): in the case of high levels of perceived social support, students' self-efficacy can effectively predict learning goals, and the establishment of learning goals is conducive to students' academic engagement (King et al., 2013). Similar to the studies described above, we expect the following:

*H3*: *Perceived social support moderates the relationship between academic self-efficacy and academic engagement.*

To sum up, we proposed a moderated mediation model (see **Figure 1**).

# MATERIALS AND METHODS

## Participants

The testers were trained in advance to ensure that they fully understood the requirements and precautions of the test. In the present study, the method of cluster sampling was used to invite all of the students of the junior high school grades 7, 8, and 9; all of the students of the senior high school grades 10 and 11; and of two schools in Hebei, China to participate in this study. They were asked to complete the questionnaires anonymously after the informed consent was obtained from the schools, teachers, and parents. Oral informed consent was obtained from each participant, and the participants were permitted to refuse to participate in the study. A total of 520 students voluntarily finished the questionnaires, of which 480 provided valid data (92.31%). Among them, 220 (45.8%) were male students, and 260 (54.2%) were female students. In age, participants ranged from 13 to 17 years, with an average age of 14.92 years ($SD = 1.47$). One-hundred and nineteen students were from grade 7, accounting for 24.8% of the total; 86 students were from grade 8, accounting for 17.9% of the total; 88 students were from grade 9, accounting for 18.3% of the total; 89 students were from grade 10, accounting for 18.5% of the total; and 98 students were from grade 11, accounting for 20.4% of the total. All materials and procedures were approved by the Research Ethics Committee of the corresponding author's institution.

## Measures

### Self-Esteem

Self-esteem was assessed using the Rosenberg's Self-Esteem Scale (RSES; Rosenberg, 1965). This scale consists of a total of 10 items rated on 4-point scales from *strongly disagree* (1) to *strongly agree* (4). The total score can range from 10 to 40, with higher scores representing higher self-esteem. In the present study, the Cronbach's alpha coefficient was 0.796, indicating an internally reliable scale.

### Academic Engagement

The Chinese version of the Utrecht Work Engagement Scale for Students (UWES-S; Gan et al., 2007) was used in this study, and the initial version was developed by Schaufeli et al. (2002). The UWES-S is a 17-item scale consisting of three factors: Vigor (six items), Dedication (five items), and Absorption (six items). Participants responded to the items on a 7-point scale from *never* (0) to *every day* (6), with higher scores representing higher levels of engagement. In the present study, the Cronbach's alpha coefficient of the total scale was high (0.943), and the Cronbach's alpha coefficients of the three subscales of Vigor, Dedication, and Absorption were 0.846, 0.843, and 0.862, respectively.

### Perceived Social Support

The Chinese version of the Perceived Social Support Scale (PSSS; Yan and Zheng, 2006) was used in this study, and the initial version was developed by Zimet et al. (1990). The PSSS is a 12-item scale that measures an individual's subjective perception of social support from family, friends, and others. Participants responded on a 7-point scale ranging from *complete disagreement* (1) to *complete agreement* (7). The total score of the PSSS ranged from 12 to 84, with the higher scores indicating higher levels of perceived social support. The Cronbach's alpha coefficient for the PSSS in our study was 0.897.

### Academic Self-Efficacy

The Chinese version of the Academic Self-Efficacy Scale (ASES; Liang, 2000) was used in this study, and the initial version was developed by Pintrich and De Groot (1990). This scale consists of a total of 22 items rated on a 5-point scale from *complete disagreement* (1) to *complete agreement* (5), with higher scores representing greater academic self-efficacy. In the present study, the Cronbach's alpha coefficient was 0.848.

## Statistical Analysis

Data were analyzed using version 22 of the Statistical Package for the Social Sciences (SPSS) and PROCESS macro 3.3 (Hayes, 2017) in this study. Before the analyses, all continuous variables were mean-centered. First, for all variables, the descriptive statistics and a bivariate correlation analysis were conducted in the SPSS. Then, PROCESS Model 4 (Hayes, 2017) was used to examine the mediating role of academic self-efficacy. Next, regarding the analysis of moderated mediation, a moderated mediation analysis was examined using PROCESS Model 14 (Hayes, 2017). Finally, we conducted a simple slope analysis to test whether the mediation effect of academic self-efficacy was different at different levels of the moderator variable. The dummy coded gender (1 = male and 2 = female) was the control variable in this analysis. Percentile bootstrap confidence intervals were calculated based on 5,000 samples.

## Check for Common Method Bias

This study adopts Harman's one-factor test (Zhou and Long, 2004) to examine common method biases. Unrotated factor analysis showed that 11 factors were generated and could explain 61.46% of the total variance. The first principal factor explained 23.4% of the variance, which is less than 40%, indicating that there was no serious common method bias in this study.

# RESULTS

## Descriptive Analyses

**Table 1** shows the means, SD, and Pearson correlations for all of the variables. Pearson correlation analyses revealed that self-esteem was positively correlated with academic engagement ($r$ = 0.23, $p < 0.01$) and academic self-efficacy ($r$ = 0.36, $p < 0.01$), and academic engagement was positively correlated with academic self-efficacy ($r$ = 0.52, $p < 0.01$).

## Testing for Mediation

**Table 2A** shows the mediation analysis results. After controlling for covariates (gender and age), the results showed that in the first step, self-esteem positively predicted academic engagement, $\beta$ = 0.23, $p < 0.001$ (Model 1 in **Table 2A**). In the second step, self-esteem positively predicted academic self-efficacy, $\beta$ = 0.36, $p < 0.001$ (Model 2 in **Table 2A**). In the third step, academic self-efficacy positively predicted academic engagement, $\beta$ = 0.47, $p < 0.001$ (Model 3 in **Table 2A**). Finally, the biased-corrected percentile bootstrap method was used to show that the indirect effect of self-esteem on academic engagement through academic self-efficacy was significant, $ab$ = 0.17, $SE$ = 0.03, and 95% CI = [0.12, 0.23], the direct effect of self-esteem on academic engagement was not significant, $c'$ = 0.06, $SE$ = 0.04, and 95% CI = [−0.03, 0.15], as shown in **Table 2B**. Therefore, academic self-efficacy fully mediated the relationship between self-esteem and academic engagement. The percentage of this mediation effect of the total effect was 73.91%. These results support Hypotheses 1 and 2 (see **Tables 2A** and **2B**; **Figure 1**).

## Testing for the Moderated Mediation Model

Model 14 of the PROCESS macro (Hayes, 2017) was used to examine the moderating role of perceived social support. Overall testing models are presented in **Figure 2**, and the specific indirect effects are presented in **Table 3A**. The results showed that self-esteem positively predicted academic self-efficacy ($\beta$ = 0.36, $p < 0.001$); academic self-efficacy positively predicted academic engagement ($\beta$ = 0.47, $p < 0.001$); self-esteem and perceived social support did not predict academic engagement ($\beta$ = 0.05, $p > 0.05$; $\beta$ = −0.01, $p > 0.05$, respectively); and the interaction effect of academic self-efficacy and perceived social support on academic engagement was significant ($\beta$ = 0.09, $p < 0.05$), and the index of the moderated mediation was 0.03, $SE$ = 0.02, 95% CI = [0.01, 0.07], indicating that the association between academic self-efficacy and academic engagement was moderated by perceived social support.

We further conducted a simple slope analysis in SPSS 22.0 to explore the pattern of the moderating effect. **Figure 3** presents

**TABLE 1** | Descriptive statistics and correlations among variables.

| | 1 | 2 | 3 | 4 | 5 | 6 |
|---|---|---|---|---|---|---|
| 1 Gender | — | | | | | |
| 2 Age | 0.11* | — | | | | |
| 3 Self-esteem | 0.03 | 0.01 | — | | | |
| 4 Academic engagement | 0.11* | −0.24** | 0.23** | — | | |
| 5 Academic self-efficacy | −0.05 | −0.19** | 0.36** | 0.52** | — | |
| 6 Perceived social support | 0.01 | −0.05 | 0.02 | 0.01 | 0.02 | — |
| *M* | 1.54 | 14.92 | 26.60 | 84.01 | 73.29 | 57.88 |
| *SD* | — | 1.47 | 2.37 | 18.90 | 10.66 | 14.61 |

*N = 480. *p < 0.05; **p < 0.01.*

**TABLE 2A** | Mediation effects of academic self-efficacy on the relationship between self-esteem and academic engagement.

| Dependent variable | Model 1 | | Model 2 | | Model 3 | |
|---|---|---|---|---|---|---|
| | $\beta$ | $t$ | $\beta$ | $t$ | $\beta$ | $t$ |
| Gender | 0.25 | 2.86** | –0.08 | –1.02 | 0.29 | 3.71*** |
| Age | –0.17 | –6.10*** | –0.13 | –4.84*** | –0.11 | –4.03*** |
| Self-esteem | 0.23 | 5.28*** | 0.36 | 8.10*** | 0.06 | 1.40 |
| Academic self-efficacy | | | | | 0.47 | 8.12*** |
| $R^2$ | 0.13 | | 0.17 | | 0.31 | |
| $F$ | 22.01*** | | 29.58*** | | 41.50*** | |

*N = 480. Each column is a regression model that predicts the criterion at the top of the column. Gender was dummy coded such that 1 = male and 2 = female. **p < 0.01; ***p < 0.001.*

**TABLE 2B** | The bootstrapping analysis of the mediating effects.

| | Effect | SE | Boot CI lower | Boot CI upper | Proportion |
|---|---|---|---|---|---|
| Total effect | 0.23 | 0.04 | 0.14 | 0.32 | |
| Direct effect | 0.06 | 0.04 | –0.03 | 0.15 | 26.09% |
| Indirect effect | 0.17 | 0.03 | 0.12 | 0.23 | 73.91% |

the perceived social support (M ± SD) as a function of academic self-efficacy and academic engagement. The results indicate that academic self-efficacy was positively correlated with academic engagement for both adolescents with higher perceived social support ($B_{\text{simple}} = 0.57$, $p < 0.001$) and also for those with lower perceived social support ($B_{\text{simple}} = 0.47$, $p < 0.001$). Moreover, bias-corrected percentile bootstrap analysis revealed that the indirect effect was more significant for adolescents with higher perceived social support – $\beta = 0.21$, $SE = 0.03$, 95% CI = [0.14, 0.27] – than for those with lower perceived social support – $\beta = 0.14$, $SE = 0.03$, 95% CI = [0.07, 0.21], as shown in **Table 3B**. In sum, these results suggested that perceived social support moderated the relationship between self-esteem and academic engagement *via* academic self-efficacy, supporting Hypothesis 3.

# DISCUSSION

The present study investigates the relationship between adolescent self-esteem and academic engagement in order to clarify how the potential mechanism of self-esteem might predict academic engagement. As expected, the results demonstrate (1) a positive association between self-esteem and academic engagement, (2) the mediating effect of academic self-efficacy, and (3) the moderating effect of perceived social support. Moreover, the mediating effect of academic self-efficacy was distinguished as being affected by different levels of perceived social support.

## Self-Esteem and Academic Engagement of Adolescents

The results show that adolescent self-esteem positively predicts academic engagement. High levels of self-esteem can increase the academic engagement of adolescents; these results support our hypothesis and validate the expectancy-value theory. Individuals with high levels of self-esteem set stricter standards and only consider themselves “good enough” when they met those standards, resulting in positive self-evaluation and increasing academic engagement (Filippello et al., 2019). From another perspective, individuals with high levels of self-esteem can effectively alleviate the negative academic emotions caused by high expectations (Kort-Butler and Hagewen, 2011).

The path coefficient between self-esteem and academic engagement was no longer significant after adding the mediating variable (academic self-efficacy), indicating that the influence of self-esteem on academic engagement was entirely through academic self-efficacy. Achievement motivation theory believes that self-esteem can significantly predict individual achievement motivation (Accordino et al., 2000), but there is an inverted U-shaped relationship between motivation level and behavior performance. Only moderate motivation can make individual behavior performance the best. Therefore, self-esteem may not directly predict adolescents’ academic engagement.

## The Mediating Role of Academic Self-Efficacy

This study found that academic self-efficacy played a complete intermediary role between adolescent self-esteem and academic engagement, which verifies our research hypothesis and echoes the research conclusions of other scholars (Pahlavani et al., 2015; Uçar and Sungur, 2017).

The self-esteem level and stability of adolescents are relatively low (Zhang et al., 2010), but most previous studies focused on the self-esteem of other ages, and few studies showed how the self-esteem of adolescents affects their academic engagement. This study shows that adolescent self-esteem does not have a direct effect on academic engagement; rather, it indirectly affects academic engagement through the influence of academic self-efficacy. Students with high self-esteem have higher self-cognition and academic self-efficacy. They can better regulate all aspects of available resources (Ouweneel et al., 2011) and thus achieve their academic expectations and ultimately increase their engagement in learning.

## The Moderating Role of Perceived Social Support

Consistent with our hypotheses, perceived social support moderated the association between academic self-efficacy and

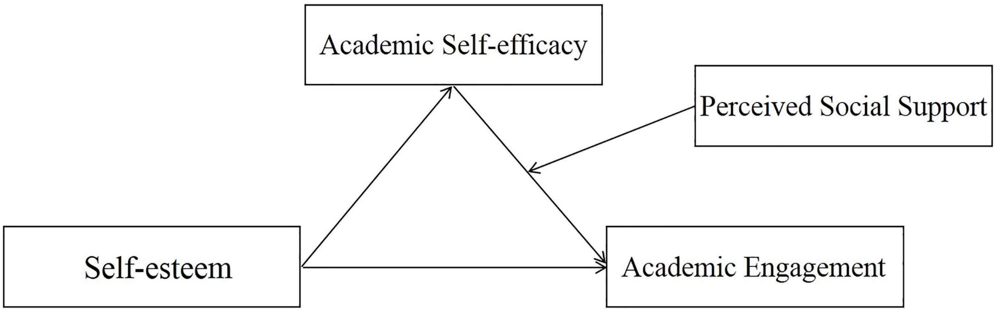


**FIGURE 1 |** The proposed moderated mediation model.

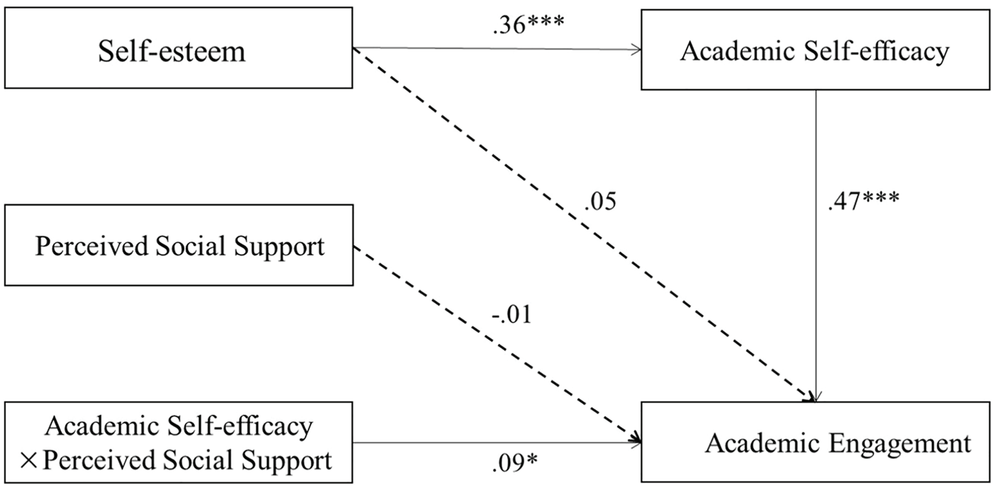


**FIGURE 2 |** Path coefficients of the moderated mediation model. Covariates were included in the model but are not presented for simplicity. *$p < 0.05$; and ***$p < 0.001$.

**TABLE 3A |** Results of perceived social support moderate the mediation process.

| Dependent variable | Model 1 | | Model 2 | |
|---|---|---|---|---|
| | *β* | *t* | *β* | *t* |
| Gender | −0.09 | −1.02 | 0.30 | 3.72*** |
| Age | −0.13 | −4.84*** | −0.11 | −4.04*** |
| Self-esteem | 0.36 | 8.10*** | 0.05 | 1.25 |
| Academic self-efficacy | | | 0.47 | 8.41*** |
| Perceived social support | | | −0.01 | −0.06 |
| Academic self-efficacy × Perceived social support | | | 0.09 | 1.97* |
| $R^2$ | 0.17 | | 0.32 | |
| *F* | 29.58*** | | 29.76*** | |

*$p < 0.05$, ***$p < 0.001$.

academic engagement. Compared with adolescents with a low level of perceived social support, the academic self-efficacy of those with a high level of perceived social support had a more significant predictive effect on academic engagement. Self-efficacy was a stable predictor of individual behavior, and academic engagement was influenced by perceived social support. The predictive effect of self-efficacy on adolescent academic engagement was changed by perceived social support.

Our findings fit with the hypothesis of the "protection factor-protection factor model" (Fergus and Zimmerman, 2005). Academic self-efficacy and perceived social support are both found to be protective factors, and the two promote and strengthen each other. The higher the level of perceived social support, the greater the predictive effect of academic self-efficacy on academic engagement. The results also validated the academic engagement impact model (Skinner and Belmont, 1993), which proposes that the satisfaction of students' basic psychological needs (autonomy, relatedness, and competence needs) directly influences their academic engagement, and that an external support system affects students' behavior by satisfying their basic psychological needs. When students establish harmonious and caring interpersonal relationships with surrounding individuals, their relatedness needs can be satisfied, which further stimulates positive behaviors such as hard work, persistence, and active participation (Legault et al., 2006). Similarly, students in classroom situations are more likely to internalize learning motivation and participate in learning activities

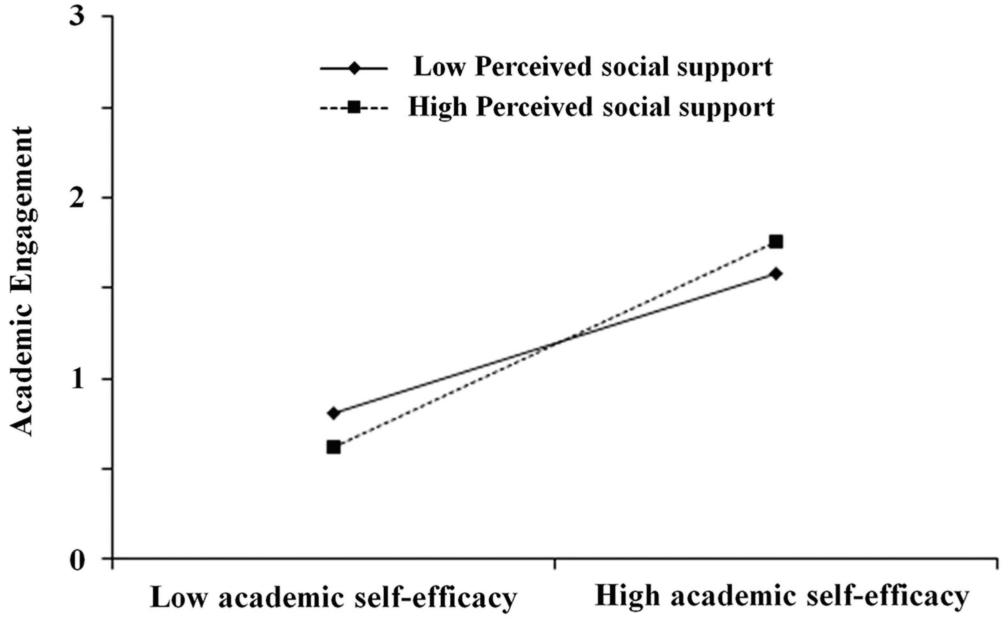


**FIGURE 3 |** Perceived social support as a moderator on the relationship between academic self-efficacy and academic engagement.

**TABLE 3B |** Conditional indirect effect of perceived social support when academic self-efficacy mediated between self-esteem and academic engagement.

| Mediator | Perceived social support | Effect | *SE* | Boot CI lower | Boot CI upper |
|---|---|---|---|---|---|
| Academic self-efficacy | M – SD | 0.14 | 0.03 | 0.07 | 0.21 |
| | M | 0.17 | 0.03 | 0.12 | 0.23 |
| | M + SD | 0.21 | 0.03 | 0.14 | 0.27 |

autonomously when they feel that their basic psychological needs are supported (Niemiec and Ryan, 2009).

This study considered the effect of perceived social support on the relationship between academic self-efficacy and academic engagement from the perspective of interpersonal relationship; however, according to different psychological theories, there may be other factors affecting academic engagement. Family investment theory believes that family socioeconomic status reflects the situation of economic capital, human capital, and social capital in the family environment comprehensively, and affects the learning attitude of students (Randolph et al., 2006). Family socioeconomic status has an impact on academic self-efficacy (Artelt et al., 2003); therefore, family socioeconomic status may also play a moderating role between academic self-efficacy and academic engagement. To sum up, the factors affecting academic engagement should be systematically investigated from different perspectives.

## LIMITATIONS AND IMPLICATIONS

There are several limitations to this study. First, the cross-sectional survey design used in the present study could not infer or verify the causal relationships among variables; a longitudinal design could be used in future studies. Second, only the self-reporting method was adopted in this study. While our results showed that there was no serious common method deviation, future research should adopt multiple research methods to collect data, such as the interview method and other evaluation methods that involve other actors (teachers, classmates, and parents). Third, due to the limitations of human and financial resources, only students in Hebei Province were selected for the test. Future research will try to sample from all of China and discuss important demographic information about the participants.

Despite the limitations of this study, it has research value and significance. This research explored the relationship among self-esteem, academic self-efficacy, perceived social support, and academic engagement. Previous studies have involved only two or three of these variables; this study used four variables to study and build a reasonable model. This work explored academic self-efficacy plays a mediating role between self-esteem and academic engagement, and it also examines the moderating role of perceived social support, further deepening our understanding of how self-esteem affects academic engagement. The model proposed in this study is helpful for educators to pay more attention to adolescents' self-esteem, academic self-efficacy, and academic engagement, so as to conduct better psychological intervention for adolescents with insufficient academic engagement.

## CONCLUSION AND RECOMMENDATIONS

This study takes an important step toward investigating the mechanism of the influence of self-esteem on academic engagement by testing a moderated mediation model. Self-esteem may positively predict adolescent academic engagement indirectly through academic self-efficacy. Perceived social support was found to be a second-stage moderator, and the mediating effect of academic self-efficacy between self-esteem and adolescents' academic engagement was found to be stronger for adolescents with higher levels of perceived social support.

Given these conclusions, we make the following recommendations. First, attention should be paid to the promotion of adolescent self-esteem and academic self-efficacy. Parents and teachers should encourage adolescents to make a positive self-cognition evaluation; they should assist them in setting reasonable learning goals and guide them to reasonable attributions of success and failure when they encounter setbacks. Second, parents and teachers should create a positive and supportive learning environment in which students feel adequately supported, encouraged, and recognized. Peer support groups that use the encouragement given by peers to make students feel part of a community of trust and support should be established. Third, parents and teachers should pay attention to the state of students' academic engagement and guide adolescents who have low academic engagement, or who seem to be exhibiting weariness and truancy. The teaching design should be novel and interesting, and the teaching method should be suitable for the needs of the students. Discussion and debate can be used to help full engage the students in the class material.

## DATA AVAILABILITY STATEMENT

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

## AUTHOR CONTRIBUTIONS

LZ contributed to conception and design of the study. YZ performed the statistical analysis and wrote the first draft of the manuscript. LZ, CP, and ZZ revised it critically for important intellectual content. ZZ collected the raw data and organized the database. All authors contributed to the article and approved the submitted version.

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BRIEF RESEARCH REPORT
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# Attitude Toward Mathematics of Future Teachers: How Important Are Creativity and Cognitive Flexibility?

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The attitude toward mathematics is shaped by cognitive components such as beliefs and cognitive processes. However, the importance of cognitive processes in attitude toward mathematics has not yet been researched. Therefore, this study aimed to identify the role of cognitive processes, creativity and cognitive flexibility, in the attitude toward mathematics of future teachers. For that purpose, 218 University students and preservice teachers, completed assignments on creativity and cognitive flexibility and a questionnaire on attitude toward mathematics. The results showed that the use of innovative details (a creativity subscale) rises the probability of exhibiting a positive attitude toward mathematics by 1.81. Besides, cognitive flexibility rises this probability by 2.32. The conclusion is that both, details and cognitive flexibility act as good predictors of a positive attitude toward mathematics. This has implications for educational practice in the planning of mathematics instruction in higher education, specifically, in future teachers.

**Keywords: attitude toward mathematics, creativity, cognitive flexibility, higher education, cognitive processes**

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## INTRODUCTION

The attitude toward mathematics is a topic that generates interest on the part of researchers due to the influence it has on student learning and performance in this subject (Pekrun et al., 2017; Sanchal and Sharma, 2017). In the scientific literature (Han and Carpenter, 2014), the attitude toward mathematics is formed by cognitive, affective and behavioral components that interact with each other. As for the cognitive component, reference is made on the one hand to beliefs about mathematics and, on the other hand, to the cognitive processes involved in the attitude toward mathematics. This research focuses on two cognitive processes that other studies (Fetterly, 2020; Riling, 2020) associate with the mathematical context, such as creativity and cognitive flexibility. Therefore, this study aimed to identify the role of creativity and cognitive flexibility in the attitude toward the mathematics of University students and future teachers.

## COGNITIVE PROCESSES IN THE ATTITUDE TOWARD MATHEMATICS

In the scientific literature, there are different definitions of attitude. Han and Carpenter (2014) establish that attitude is an affective, cognitive, and behavioral reaction to an environment or object, while for Rodríguez et al. (2020) attitude toward mathematics refers to beliefs about the effectiveness and interest of students in performing mathematical tasks in academic and everyday situations. In this study, the attitude toward mathematics is the disposition of a person toward a mathematical task resulting from his/her way of thinking, feeling, or acting.

Regarding the development of attitude, Han and Carpenter (2014) indicate that attitude toward mathematics is formed by cognitive, affective, and behavioral components that interact with each other. According to these authors, the cognitive component comprises what is believed or thought about mathematics, the affective component is the feeling or emotion toward mathematics, and the behavioral component is the tendency to respond to mathematical learning. In this line, the models of attitude toward mathematics (Abraham et al., 2010; Di Martino and Zan, 2015) obtained through qualitative methods confirm the participation of both cognitive and non-cognitive (affective and behavioral) components. The cognitive component of the attitude toward mathematics is consisting of, on the one hand, the beliefs about mathematics, and on the other hand, the cognitive processes involved in that. Beliefs about mathematics have been widely studied in the literature. They refer to psychologically-based propositions about mathematics that are believed to be true (Philipp, 2007). Nonetheless, the cognitive processes involved in the attitude toward mathematics have been scarcely studied. The research found relates the attitude toward mathematics to reasoning skills (Lipnevich et al., 2016), decision-making (Rolison et al., 2020), cognitive reflection (Morsanyi et al., 2014), and creativity (Sharma, 2014). Specifically, in the mathematical context, researchers pay more attention to creativity, which is considered as an action in the Creative Mathematics Action Framework (Riling, 2020) and as a thought process or product manifested in fluidity, cognitive flexibility, and originality (Fetterly, 2020). Therefore, creativity is connected to the attitude toward mathematics through actions involving mathematics. However, up to date, there is a lack of models explaining how creativity, as a cognitive process that is part of the cognitive component of the mathematical attitude, influences this attitude toward mathematics. Besides, research is found such as Mann (2005) study, which finds an association between positive attitude toward mathematics and greater creativity, and Nijstad's two-way model of creativity, and Nijstad et al. (2010) reflect that the activation of positive moods enhances creativity through the stimulation of cognitive flexibility. In this model (Nijstad et al., 2010), one of the ways to be creative is through cognitive flexibility, emphasizing that a key component of creativity is cognitive flexibility or the ability to adopt different perspectives, an approach also supported by other authors (Vartanian, 2009; Zabelina and Robinson, 2010; Haavold, 2021).

In the mathematical context, cognitive flexibility is a critical issue in problem solving. Clément (2006) understands it as the ability to select from various perspectives or strategies. Heinze et al. (2009) reflect the relevance of cognitive flexibility in interpreting situations or in using mathematical strategies, and Vartanian (2009) evidence that cognitive flexibility confers advantages on creative people in problem solving because changes in the structure of a problem require the necessary adjustments in problem-solving strategies. The theory of cognitive flexibility (Spiro et al., 2003) emphasizes that cognitive flexibility is necessary to address a mathematical concept (Jonassen, 2011), and as a teacher, cognitive flexibility facilitates the creation of learning scenarios considering different perspectives (Valentine and Kopcha, 2016).

In this study, we focus on University students and specifically on future teachers. The reason is that these students will be teaching mathematics in their future lives, and the mathematics instruction they will carry out will be influenced by their attitude toward mathematics (Raymond, 1997) and will subsequently affect the perception of mathematics of their future students and so their achievement (Bekdemir, 2010; Cardetti and Truxaw, 2014) and performance in the subject. Some studies show the connection between mathematics teaching and the attitudes of students toward this subject (Rojas and Deulofeu, 2015) and the influence of the attitude of the mathematics teacher on the performance of the student in mathematics (Desimone, 2009). Regarding the specific results of the research carried out with University students, Bates et al. (2011) find that the future teachers are the University group with more negative attitudes toward mathematics and Cargnelutti et al. (2017) show the presence of mathematical anxiety in the future teachers, that this persists over time, and negatively influences student learning and performance.

Research has shown that basing mathematics education on transmission leads to limited and biased conceptions in this field. This has generated an interest in creating learning environments where mathematical concepts and processes are transmitted (Kisa and Stein, 2015). Dimmel and Herbst (2017) point out the need for a positive attitude toward mathematics among teachers to incorporate active and innovative learning scenarios in their classrooms. In this line, we consider it crucial for future teachers, on the one hand, to be aware that his or her attitude toward mathematics affects the attitudes and/or performance of students, and on the other, that the mathematical attitude is made up of cognitive components that can be known and promoted from their parts, such as creativity and cognitive flexibility. With this knowledge, future teachers would design instructional proposals by using their creativity and cognitive flexibility, which will be aimed at students having positive experiences with mathematics and so improving the mathematical attitude and performance of students.

This research hypothesizes that the cognitive components (creativity and cognitive flexibility) are related to the attitude toward mathematics in a specific population such as University students who become mathematics teachers. In this study, tests were used to evaluate creative potential and cognitive flexibility from a generic point of view, without directly referring to mathematical competencies. The aim was to use simple tests with stable psychometric properties for the general population, without being conditioned to a certain level of mathematical competence. In addition, in the case of creativity, tests evaluating divergent thinking based primarily on the originality and innovation of proposals have been reviewed as a way of assessing the creative potential. This way of evaluating creativity is considered to be a predictor of future success even if one has no solid knowledge in a particular field (Runco and Acar, 2012).

# METHODS

## Participants

The sample consisted of 218 University students (77.1% women and 22.9% men, with an age range of 17–47 years, $M = 19.7$, $SD = 2.71$). Out of that, 114 were first-year students and 104 were second-year students. All the participants have taken mathematics subjects in addition to other subjects in the education major. The inclusion criteria were to be students of Education, to be over 18 years old at the time of taking the test, to be enrolled in a mathematics-related subject, and not to have taken the tests previously.

## Materials

The instruments applied in the research were:

Modified Attitude toward mathematics scale (Auzmendi, 1992; Fernández-Cézar et al., 2016). It is a test composed of 10 items that evaluate the degree of agreement and disagreement by a 5-point Likert scale. The items are statements dealing with thoughts and emotions toward mathematics. The internal consistency evaluated with Cronbach's α offered by the authors is 0.91 (Fernández-Cézar et al., 2016), which coincides with the obtained sample of this study.

Creative Imagination Test for Adults (PIC-A) (Artola et al., 2012) assesses the creative potential of students through four tasks and provides information on eight scales (fluency, flexibility, narrative originality, fantasy, graphic originality, elaboration, special details, and title) and three creativity indexes (narrative, graphic, and general). The meaning of scales and indexes is as follows: fluidity, as the capacity for ideas production; flexibility, as the capacity to produce answers varied in type and topics; narrative originality, as innovative narrative answers; graphic originality, as innovative answers from a graphic representation; fantasy, referred to the generation of ideas from offered data; elaboration, as the descriptive presentation of the ideas; special details, as the use of innovative details; title, as the capacity to put special titles to the narrated or represented ideas; narrative creativity (innovative verbal proposals composed of the fantasy, fluidity, flexibility, and creative originality scales), and graphic creativity (innovative non-verbal proposals composed of the graphic originality, elaboration, special details, and title scales), and the general creativity index (sum of narrative and graphic creativity, and indicator of the creative potential to generate new and original ideas). The internal consistency (Cronbach's α) offered by the authors is 0.83, while it is 0.78 for this study sample.

Changes Test (Seisdedos Cubero, 1994) assesses the cognitive flexibility in adults through a simple geometric figure task in which the response must match under the change of different parameters. The internal consistency for this sample (Cronbach's α) is 0.87.

## Procedure

About 3 days were scheduled to administer the tests that were completed in the respective classrooms of students. There were three class groups and each student was delivered a paper test. First, they completed the creativity task, which was followed by the cognitive flexibility and attitude toward mathematics tests, respectively. The time taken for the test in each classroom was approximately 70 min and the first author was in charge of administering the tests to the students. Prior to taking the test, all the University students (adults) signed written consent, were informed that the participation was voluntary and had withdrawal possibility at any stage. All the data were collected in compliance with the ethical guidelines of the Helsinki Declaration and the confidentiality of the data was guaranteed. The research was revised and approved by the Asociación Educar para el Desarrollo Humano Ethics Commission.

**TABLE 1 |** Mean (M) and SD for cognitive flexibility, mathematical attitude, creativity, and matrix correlation.

| | Mean *(M)* | Standard deviation *(SD)* | Correlations with mathematical attitude |
|---|---|---|---|
| Cognitive flexibility | 13.20 | 6.30 | −0.251** |
| Mathematical attitude | 29.40 | 9.12 | 1 |
| Fantasy | 5.22 | 3.23 | 0.122 |
| Fluency | 30.63 | 10.42 | −0.024 |
| Flexibility | 18.40 | 4.88 | −0.017 |
| Narrative originality | 6.47 | 4.34 | −0.083 |
| Graphic originality | 1.99 | 1.62 | −0.013 |
| Elaboration | 2.03 | 1.67 | −0.053 |
| Details | 2.11 | 1.72 | −0.135* |
| Title | 0.803 | 1.28 | −0.070 |
| Narrative creativity | 58.59 | 19.45 | −0.033 |
| Graphic creativity | 6.90 | 4.29 | −0.098 |
| Total creativity | 65.46 | 21.04 | −0.049 |

*$p < 0.05$; **$p < 0.001$.

## Data Analysis

The Social Science Statistical Package, SPSS (Windows version 25), was used to carry out the analyses. Descriptive statistics were used to find out the means and SD of the studied variables. Provided the sample size, the Kolmogorov-Smirnoff test was used for normality, obtaining $p < 0$ for all of them which requires the use of non-parametric coefficients and inferential test (López-Roldán and Fachelli, 2015; Montgomery, 2017). Therefore, to obtain the correlations between the variables, the Spearman coefficient was used. The variables, cognitive flexibility (evaluated with Changes Test) and creativity components (evaluated with PIC-A Test) were then categorized by taking into account the mean plus half the SD as the cutoff point. Finally, a binary logistic regression was performed with attitude toward mathematics as the dependent variable, to identify its predictors among the studied variables. Hosmer-Lemeshow test was considered for model goodness-of-fit.

# RESULTS

The first step was to carry out the descriptive analysis by means of central tendency and dispersion indexes of the variables, obtaining that the cognitive flexibility task was within the average

**TABLE 2 |** Mean (M) and SD of categorized variables by media and plus half SD.

| | Low level | | High level | |
|---|---|---|---|---|
| | Mean *(M)* | Standard deviation *(SD)* | Mean *(M)* | Standard deviation *(SD)* |
| Cognitive flexibility | 9.51 | 3.70 | 20.43 | 3.39 |
| Creativity | | | | |
| Fantasy | 3.83 | 1.88 | 9.90 | 2.28 |
| Fluency | 29.79 | 9.28 | 60.16 | 2.13 |
| Flexibility | 16 | 2.94 | 24.18 | 3.63 |
| Narrative originality | 5.88 | 3.8 | 13 | 4.3 |
| Graphic originality | 1.82 | 1.38 | 6.3 | 1.06 |
| Elaboration | 1.70 | 1.20 | 6.18 | 1.04 |
| Details | 0.59 | 1.04 | 6.25 | 1.50 |
| Title | 0.70 | 1.04 | 6.25 | 1.50 |
| Narrative creativity | 47.77 | 10.98 | 81.48 | 12.25 |
| Graphic creativity | 3.25 | 1.42 | 9.62 | 3.65 |
| Total creativity | 53.73 | 11.64 | 90.78 | 12.88 |

according to the scales of the test (Seisdedos Cubero, 1994). The attitude toward mathematics at a moderately negative level and the general creativity and creativity indexes at a low level in comparison with the scales were offered by the authors of the assessment instrument (Artola et al., 2012; **Table 1**).

The next step was to examine the relationship between attitude toward mathematics and flexibility and creativity finding that mathematical attitude had a negative and statistically significant relationship with cognitive flexibility ($r = -0.251$, $p < 0$) and details ($r = –0.135$, $p < 0.05$; **Table 1**). To analyze the effect of cognitive-affective variables on the attitude toward mathematics, taking into account that the independent variables do not meet normality criteria, we conducted a binomial logistic regression analysis with attitude toward mathematics as the categorical outcome and the high level as the contrast group. Cognitive flexibility and details were included as predictors, assuming the high level as the reference. The descriptive statistics of categorized variables are presented in **Table 2**. The differences in attitude toward mathematics between the high-low groups are significant ($U = 10.65$, $p < 0$, $d = 1.66$). In addition, the value of the effect size is high (Cohen's $d > 0.80$), being able to state that the differences are due to high-low groups (Cohen et al., 2018).

The Omnibus test is significant, which indicates that the dependent variable (attitude toward mathematics) is explained by at least one variable ($\chi^2 = 12.78$, $p < 0.05$). The results of the analysis are presented in **Table 3**, including odds ratio (ORs) and the 95% of confidence interval for each predictor. ORs reflect the increase (or decrease) in the odds of a participant being in the contrast group relative to the high attitude toward the mathematics group based on the change among categories for each predictor. In the predictors, the high category has also been taken as the reference.

The Hosmer-Lemeshow value is 0.59, well above 0.05, exhibiting more than a reasonable goodness-of-fit ($\chi^2 = 1.05$, $p = 0.59$). In the proposed model, the chance of participants belonging to the high attitude toward mathematics group is 61%.

We will illustrate the interpretation of the OR for the cognitive flexibility in the comparison of the high to the low attitude toward mathematics groups, from data in **Table 3**. The OR represents the change in the odds of being in the low compared to high attitude toward mathematics group, which mathematically is got as 1/expB. In this case, it is 2.32 (1/0.430) to cognitive flexibility which means that the odds for participants with low cognitive flexibility to belong to the low attitude toward mathematics group was 2.32 times more likely than for participants with high cognitive flexibility. In the same way, 1.81 (1/0.552) to details (subscale of PIC-A and creativity test) means that a participant with a low score in details is 1.81 times more likely to have a low attitude toward mathematics than a participant with a high score in details (use of innovative details).

## DISCUSSION

This study aimed to identify the role of cognitive processes, creativity, and cognitive flexibility, in the attitude toward the mathematics of future teachers. For that purpose, 218 University students and preservice teachers completed assignments on creativity and cognitive flexibility and a questionnaire on attitude toward mathematics.

The results confirm the relationship between creativity (use of innovative details) with mathematical attitude in future teachers. These results are in the direction of those found by Mann (2005) for creativity which does indicate a relationship with the attitude toward mathematics.

Furthermore, in this study, a significant negative relationship has been obtained between the attitude toward mathematics and cognitive flexibility. Specifically, the study indicates that those students who have a negative attitude toward mathematics are less able to adopt different perspectives on mathematical facts, situations, or problems. The connection between cognitive flexibility and the attitude toward mathematics is a novel finding that must be deeply explored in future research.

In this sense, the data obtained are congruent with those provided by other investigations that show the relevance of cognitive flexibility in problem solving (Clément, 2006; Heinze et al., 2009; Vartanian, 2009; Cragg and Gilmore, 2014). An interpretation of that could be that cognitive flexibility allows adaptation and problem solving in an adaptive way, a relevant aspect in the work of the teacher. The results suggest that cognitive flexibility is a variable to be considered in the attitude toward the mathematics of future teachers. In this direction, authors such as Dimmel and Herbst (2017) and Valentine and Kopcha (2016) suggest that to teach mathematics actively and innovatively, future teachers need cognitive flexibility and a positive attitude toward mathematics. Therefore, by promoting the cognitive flexibility of future University teachers, a more positive attitude toward mathematics can be fostered, and, consequently, in the long run, the transmission to their pupils can be achieved through the creation of different learning

**TABLE 3 |** Model of logistic regression for the attitude toward mathematics.

| | B | Wald | Sig | Exp (B) | IC 95% Exp (B) lower-higher |
|---|---|---|---|---|---|
| Cognitive flexibility* | −0.843 | 7.949 | 0.005 | 0.430 | 0.240–0.773 |
| Details* (subescale of creativity) | −0.595 | 4.478 | 0.039 | 0.552 | 0.318–0.957 |

*$p < 0.05$.

scenarios that affect the attitude of students toward the subject of mathematics (Rojas and Deulofeu, 2015).

As pointed out by different authors, cognitive flexibility is the ability to select various strategies in solving problems, a critical issue in the mathematics context (Clément, 2006; Heinze et al., 2009; Vartanian, 2009). Thus, in this research, we consider that for a future teacher, the more creative and flexible they are in formulating mathematics proposals, the more positive attitude toward mathematics they exhibit. It will redound for their future students in a more effective way to get an insight into mathematics (Jonassen, 2011) which will entail a more effective performance.

The educational implication derived from this research is two-fold. On the one hand, a main theoretical implication is revealed: cognitive flexibility influences the attitude toward mathematics in future teachers. The positive attitudes of teachers, embedded in their teaching practice, can help students in the early stages of education to actively build their learning and improve their mathematics achievement. Following this line, the positive attitude of teachers toward mathematics would be reflected in, or provoke, positive emotions that contribute to the development of adaptive coping styles that, in turn, are related to the development of cognitive flexibility (Seligman et al., 2005). In this area, more research is needed. On the other hand, a significant practical implication is inferred: the planning of mathematics instruction incorporating the work on the attitudes toward the mathematics of future teachers, the consideration of cognitive flexibility in the creation of teaching activities, and the use of innovative details. All that should be intended to generate positive attitudes in a population as crucial as future teachers are because this way they could become educational models with mathematical attitudes that they will possibly transmit to their future students (Cardetti and Truxaw, 2014). The attitude is fundamental to foster mathematical competence (Dowker et al., 2019) and constitutes a learned predisposition that affects the construction of the person itself, and the knowledge, being learned and susceptibly improved. The present investigation has several limitations. Thus, due to the sampling characteristics and the lack of control of foreign variables, it is necessary to be cautious in the generalization of results. This study points toward future lines of research in which the analysis of the influence of cognitive processing on the attitude toward mathematics allows a better quality of competence in the mathematics teachers, with consequences in students in the lower educational stages. The results suggest that cognitive flexibility and the use of innovative details can predict the attitude toward mathematics. On the contrary, at least in the sample of this study and with the assessment instruments used, it seems that creativity (except for the details subscale) is not a cognitive variable that can predict such attitude. As future action lines, the selection of the sample randomly among different universities is pointed out, and the control of different variables could be predictive of the mathematical attitude. Although in this study the evaluation of creativity and cognitive flexibility was intended generically, in future studies, the use of tests associated with the mathematical field can be considered, creating in such case homogeneous subgroups in relation to the mathematical competence to contrast possible differences in the cognitive variables. For example, other cognitive variables such as the perceived self-efficacy in mathematical tasks, the evaluation of the mathematical reasoning skills, or the creative potential in logical-mathematical thinking should be considered. In addition, a longitudinal design could be used to know how the relationship between the variables evolves throughout University teacher training courses. Therefore, taking into account the different considerations, the involvement of cognitive variables and the attitude toward mathematics in future teachers can be reflected with greater empirical accuracy.

## 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 Asociación Educar para el Desarrollo Humano Ethics Commission. The patients/participants provided their written informed consent to participate in this study.

## AUTHOR CONTRIBUTIONS

Cd-l-P, RF-C, and NS-P contributed to design of the study. Cd-l-P collected data and corrected the filled in tests. NS-P and RF-C performed the statistical analysis. Cd-l-P wrote the first draft of the manuscript. NS-P wrote manuscript Methods and Results sections. All authors contributed to manuscript revision, read, and approved the submitted version.

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SYSTEMATIC REVIEW
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# Levels of Reading Comprehension in Higher Education: Systematic Review and Meta-Analysis

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Higher education aims for university students to produce knowledge from the critical reflection of scientific texts. Therefore, it is necessary to develop a deep mental representation of written information. The objective of this research was to determine through a systematic review and meta-analysis the proportion of university students who have an optimal performance at each level of reading comprehension. Systematic review of empirical studies has been limited from 2010 to March 2021 using the Web of Science, Scopus, Medline, and PsycINFO databases. Two reviewers performed data extraction independently. A random-effects model of proportions was used for the meta-analysis and heterogeneity was assessed with $I^2$. To analyze the influence of moderating variables, meta-regression was used and two ways were used to study publication bias. Seven articles were identified with a total sample of the seven of 1,044. The proportion of students at the literal level was 56% (95% CI = 39–72%, $I^2$ = 96.3%), inferential level 33% (95% CI = 19–46%, $I^2$ = 95.2%), critical level 22% (95% CI = 9–35%, $I^2$ = 99.04%), and organizational level 22% (95% CI = 6–37%, $I^2$ = 99.67%). Comparing reading comprehension levels, there is a significant higher proportion of university students who have an optimal level of literal compared to the rest of the reading comprehension levels. The results have to be interpreted with caution but are a guide for future research.

**Keywords: reading comprehension, higher education, university students, systematic review, meta-analysis**

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## INTRODUCTION

Reading comprehension allows the integration of knowledge that facilitates training processes and successful coping with academic and personal situations. In higher education, this reading comprehension has to provide students with autonomy to self-direct their academic-professional learning and provide critical thinking in favor of community service (UNESCO, 2009). However, research in recent years (Bharuthram, 2012; Afflerbach et al., 2015) indicates that a part of university students are not prepared to successfully deal with academic texts or they have reading difficulties (Smagorinsky, 2001; Cox et al., 2014), which may limit academic training focused on written texts. This work aims to review the level of reading comprehension provided by studies carried out in different countries, considering the heterogeneity of existing educational models.

The level of reading comprehension refers to the type of mental representation that is made of the written text. The reader builds a mental model in which he can integrate explicit and implicit data from the text, experiences, and previous knowledge (Kucer, 2016; van den Broek et al., 2016). Within the framework of the construction-integration model (Kintsch and van Dijk, 1978; Kintsch, 1998), the most accepted model of reading comprehension, processing levels are differentiated, specifically: A superficial level that identifies or memorizes data forming the basis of the text and a deep level in which the text situation model is elaborated integrating previous experiences and knowledge. At these levels of processing, the cognitive strategies used, are different according to the domain-learning model (Alexander, 2004) from basic coding to a transformation of the text. In the scientific literature, there are investigations (Yussof et al., 2013; Ulum, 2016) that also identify levels of reading comprehension ranging from a literal level of identification of ideas to an inferential and critical level that require the elaboration of inferences and the data transformation.

Studies focused on higher education (Barletta et al., 2005; Yáñez Botello, 2013) show that university students are at a literal or basic level of understanding, they often have difficulties in making inferences and recognizing the macrostructure of the written text, so they would not develop a model of a situation of the text. These scientific results are in the same direction as the research on reading comprehension in the mother tongue in the university population. Bharuthram (2012) indicates that university students do not access or develop effective strategies for reading comprehension, such as the capacity for abstraction and synthesis-analysis. Later, Livingston et al. (2015) find that first-year education students present limited reading strategies and difficulties in understanding written texts. Ntereke and Ramoroka (2017) found that only 12.4% of students perform well in a reading comprehension task, 34.3% presenting a low level of execution in the task.

Factors related to the level of understanding of written information are the mode of presentation of the text (printed vs. digital), the type of metacognitive strategies used (planning, making inferences, inhibition, monitoring, etc.), the type of text and difficulties (novel vs. a science passage), the mode of writing (text vs. multimodal), the type of reading comprehension task, and the diversity of the student. For example, several studies (Tuncer and Bahadir, 2014; Trakhman et al., 2019; Kazazoglu, 2020) indicate that reading is more efficient with better performance in reading comprehension tests in printed texts compared to the same text in digital and according to Spencer (2006) college students prefer to read in print vs. digital texts. In reading the written text, metacognitive strategies are involved (Amril et al., 2019) but studies (Channa et al., 2018) seem to indicate that students do not use them for reading comprehension, specifically; Korotaeva (2012) finds that only 7% of students use them. Concerning the type of text and difficulties, for Wolfe and Woodwyk (2010), expository texts benefit more from the construction of a situational model of the text than narrative texts, although Feng (2011) finds that expository texts are more difficult to read than narrative texts. Regarding the modality of the text, Mayer (2009) and Guo et al. (2020) indicate that multimodal texts that incorporate images into the text positively improve reading comprehension. In a study of Kobayashi (2002) using open questions, close, and multiple-choice shows that the type and format of the reading comprehension assessment test significantly influence student performance and that more structured tests help to better differentiate the good ones and the poor ones in reading comprehension. Finally, about student diversity, studies link reading comprehension with the interest and intrinsic motivation of university students (Cartwright et al., 2019; Dewi et al., 2020), with gender (Saracaloglu and Karasakaloglu, 2011), finding that women present a better level of reading comprehension than men and with knowledge related to reading (Perfetti et al., 1987). In this research, it was controlled that all were printed and unimodal texts, that is, only text. This is essential because the cognitive processes involved in reading comprehension can vary with these factors (Butcher and Kintsch, 2003; Xu et al., 2020).

## THE PRESENT STUDY

Regardless of the educational context, in any university discipline, preparing essays or developing arguments are formative tasks that require a deep level of reading comprehension (inferences and transformation of information) that allows the elaboration of a situation model, and not having this level can lead to limited formative learning. Therefore, the objective of this research was to know the state of reading comprehension levels in higher education; specifically, the proportion of university students who perform optimally at each level of reading comprehension. It is important to note that there is not much information about the different levels in university students and that it is the only meta-analytic review that explores different levels of reading comprehension in this educational stage. This is a relevant issue because the university system requires that students produce knowledge from the critical reflection of scientific texts, preparing them for innovation, employability, and coexistence in society.

## MATERIALS AND METHODS

### Eligibility Criteria: Inclusion and Exclusion

Empirical studies written in Spanish or English are selected that analyze the reading comprehension level in university students.

The exclusion criteria are as follows: (a) book chapters or review books or publications; (b) articles in other languages; (c) studies of lower educational levels; (d) articles that do not identify the age of the sample; (e) second language studies; (f) students with learning difficulties or other disorders; (g) publications that do not indicate the level of reading comprehension; (h) studies that relate reading competence with other variables but do not report reading comprehension levels; (i) pre-post program application work; (j) studies with experimental and control groups; (k) articles comparing pre-university stages or adults; (l) publications that use multi-texts; (m) studies that use some type of technology (computer, hypertext, web, psychophysiological, online questionnaire, etc.); and (n) studies unrelated to the subject of interest.

Only those publications that meet the following criteria are included as: (a) be empirical research (article, thesis, final degree/master's degree, or conference proceedings book); (b) university stage; (c) include data or some measure on the level of reading comprehension that allows calculating the effect size; (d) written in English or Spanish; (e) reading comprehension in the first language or mother tongue; and (f) the temporary period from January 2010 to March 2021.

## Search Strategies

A three-step procedure is used to select the studies included in the meta-analysis. In the first step, a review of research and empirical articles in English and Spanish from January 2010 to March 2021. The search is carried out in online databases of languages in Spanish and English, such as Web of Science (WoS), Scopus, Medline, and PsycINFO, to review empirical productions that analyze the level of reading comprehension in university students. In the second step, the following terms (titles, abstracts, keywords, and full text) are used to select the articles: Reading comprehension and higher education, university students, in Spanish and English, combined with the Boolean operators AND and OR. In the last step, secondary sources, such as the Google search engine, Theseus, and references in publications, are explored.

The search reports 4,294 publications (articles, theses, and conference proceedings books) in the databases and eight records of secondary references, specifically, 1989 from WoS, 2001 from Scopus, 42 from Medline, and 262 of PsycINFO. Of the total (4,294), 1,568 are eliminated due to duplications, leaving 2,734 valid records. Next, titles and abstracts are reviewed and 2,659 are excluded because they do not meet the inclusion criteria. The sample of 75 publications is reduced to 40 articles, excluding 35 because the full text cannot be accessed (the authors were contacted but did not respond), the full text did not show specific statistical data, they used online questionnaires or computerized presentations of the text. Finally, seven articles in Spanish were selected for use in the meta-analysis of the reading comprehension level of university students. Data additional to those included in the articles were not requested from the selected authors.

The PRISMA-P guidelines (Moher et al., 2015) are followed to perform the meta-analysis and the flow chart for the selection of publications relevant to the subject is exposed (**Figure 1**).

## Encoding Procedure

This research complies with what is established in the manual of systematic reviews (Higgins and Green, 2008) in which clear objectives, specific search terms, and eligibility criteria for previously defined works are established. Two independent coders, reaching a 100% agreement, carry out the study search process. Subsequently, the research is codified, for this, a coding protocol is used as a guide to help resolve the ambiguities between the coders; the proposals are reflected and discussed and discrepancies are resolved, reaching a degree of agreement between the two coders of 97%.

For all studies, the reference, country, research objective, sample size, age and gender, reading comprehension test, other tests, and reading comprehension results were coded in percentages. All this information was later systematized in **Table 1**.

In relation to the type of reading comprehension level, it was coded based on the levels of the scientific literature as follows: 1 = literal; 2 = inferential; 3 = critical; and 4 = organizational.

Regarding the possible moderating variables, it was coded if the investigations used a standardized reading comprehension measure (value = 1) or non-standardized (value = 0). This research considers the standardized measures of reading comprehension as the non-standardized measures created by the researchers themselves in their studies or questionnaires by other authors. By the type of evaluation test, we encode between multiple-choice (value = 0) or multiple-choices plus open question (value = 1). By type of text, we encode between argumentative (value = 1) or unknown (value = 0). By the type of career, we encode social sciences (value = 1) or other careers (health sciences; value = 0). Moreover, by the type of publication, we encode between article (value = 1) or doctoral thesis (value = 0).

## Effect Size and Statistical Analysis

This descriptive study with a sample $k = 7$ and a population of 1,044 university students used a continuous variable and the proportions were used as the effect size to analyze the proportion of students who had an optimal performance at each level of reading comprehension. As for the percentages of each level of reading comprehension of the sample, they were transformed into absolute frequencies. A random-effects model (Borenstein et al., 2009) was used as the effect size. These random-effects models have a greater capacity to generalize the conclusions and allow estimating the effects of different sources of variation (moderating variables). The DerSimonian and Laird method (Egger et al., 2001) was used, calculating raw proportion and for each proportion its standard error, value of $p$ and 95% confidence interval (CI).

To examine sampling variability, Cochran's $Q$ test (to test the null hypothesis of homogeneity between studies) and $I^2$ (proportion of variability) were used. According to Higgins et al. (2003), if $I^2$ reaches 25%, it is considered low, if it reaches 50% and if it exceeds 75% it is considered high. A meta-regression analysis was used to investigate the effect of the moderator variables (type of measure, type of evaluation test, type of text, type of career, and type of publication) in each level of reading comprehension of the sample studies. For each moderating variable, all the necessary statistics were calculated (estimate, standard error, CI, $Q$, and $I^2$).

To compare the effect sizes of each level (literal, inferential, critical, and organizational) of reading comprehension, the chi-square test for the proportion recommended by Campbell (2007) was used.

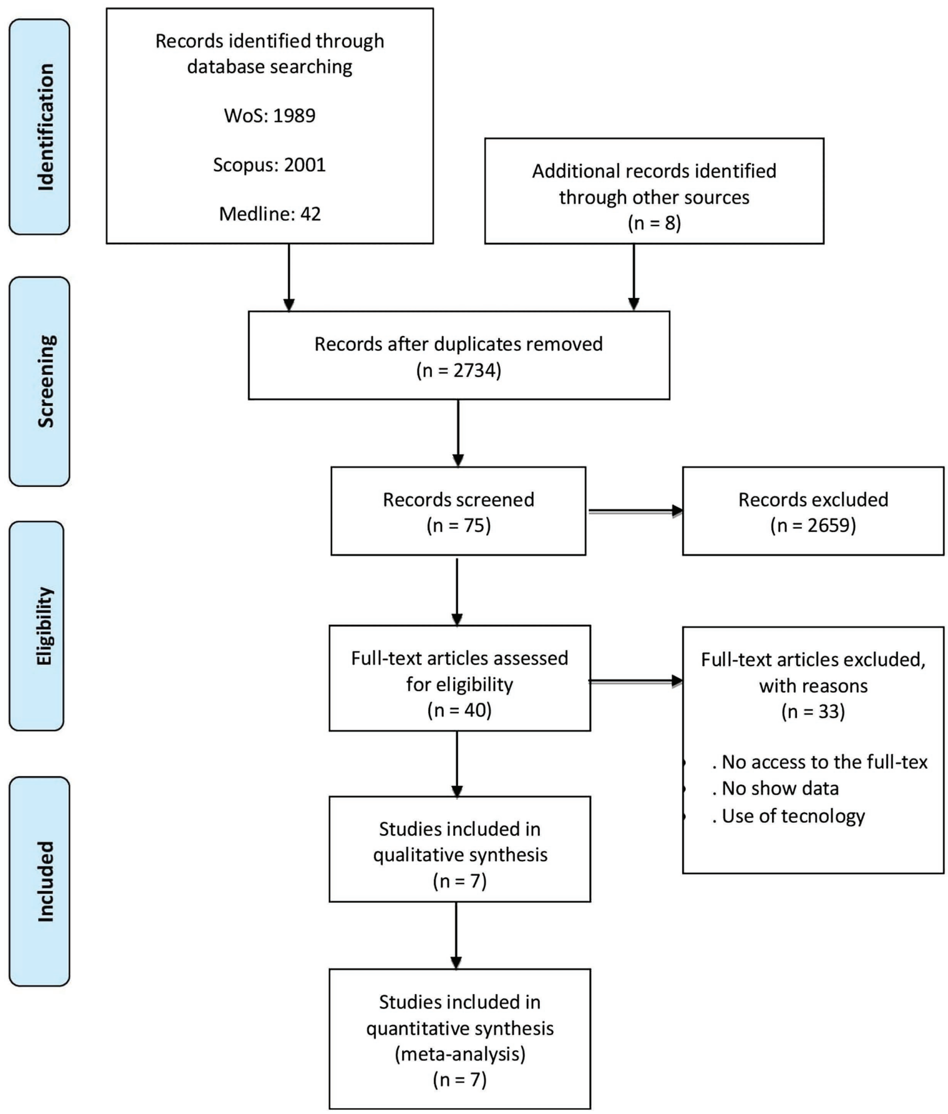


**FIGURE 1** | Flow diagram for the selection of articles.

Finally, to analyze publication bias, this study uses two ways: Rosenthal's fail-safe number and regression test. Rosenthal's fail-safe number shows the number of missing studies with null effects that would make the previous correlations insignificant (Borenstein et al., 2009). When the values are large there is no bias. In the regression test, when the regression is not significant, there is no bias.

The software used to classify and encode data and produce descriptive statistics was with Microsoft Excel and the Jamovi version 1.6 free software was used to perform the meta-analysis.

## RESULTS

The results of the meta-analysis are presented in three parts: the general descriptive analysis of the included studies; the meta-analytic analysis with the effect size, heterogeneity, moderating variables, and comparison of effect sizes; and the study of publication bias.

### Overview of Included Studies

The search carried out of the scientific literature related to the subject published from 2010 to March 2021 generated a small number of publications, because it was limited to the higher education stage and required clear statistical data on reading comprehension.

**Table 1** presents all the publications reviewed in this meta-analysis with a total of students evaluated in the reviewed works that amounts to 1,044, with the smallest sample size of 30 (Del Pino-Yépez et al., 2019) and the largest with 570 (Guevara Benítez et al., 2014). Regarding gender, 72% women and 28% men were included. Most of the sample comes

**TABLE 1** | Results of the empirical studies included in the meta-analysis.

| S. No. | Reference | Country | Objective | Sample (*n*°/age/sex) | Comprehension Instrumentos | Other tests | Reading comprehension results |
|---|---|---|---|---|---|---|---|
| 1. | Del Pino-Yépez et al., 2019 | Ecuador | Assess the effectiveness of didactic strategies to strengthen the level of reading comprehension | 30 Educación/unknown/unknown | *Ad hoc* text with 12SS questions | | Literal: 40% Inferential: 40% Critical: 20% |
| 2. | Guevara Benítez et al., 2014 | México | Validate reading comprehension test | 570 Psychology/19.9 years/72% women 28% men | Instrument to measure reading comprehension of university students (ICLAU) | | Literal: 41% Inferential: 33% Critical: 47% Appreciative: 72% Organization.: 75% Prueba general: 66% |
| 3. | Sáez Sánchez, 2018 | México | Assess reading comprehension | 101 Education/unknown/unknown | *Ad hoc* text with questions | | Literal: 52.86% Inferential: 52.92% Critical: 53.89% Organization: 66.46% Appreciative: 44.01% |
| 4. | Sanabria Mantilla, 2018 | Bolivia | Identify the relationship between reading comprehension and academic performance | 49 Psychology/18.5 years/87.8% women 12.2% men | Instrument to measure reading comprehension in university students (ICLAU) | Academic qualifications | Literal: 67.3% Inferential: 12.2% Organization: 4.1% Critical: 0% Appreciative: 0% |
| 5. | Márquez et al., 2016 | Chile | Know the level of reading comprehension | 44 Kinesiology and Nutrition and Dietetics/unknown/unknown | Instrument to measure reading comprehension in university students (ICLAU) | | Literal: 43.2% Inferential: 4.5% Critical: 0% Organization: 4.5% |
| 6. | Yáñez Botello, 2013 | Colombia | Characterize the cognitive processes involved in reading and their relationship with reading comprehension levels | 124 Psychology/16–30 years/unknown | Arenas Reading Comprehension Assessment Questionnaire (2007) | | Literal: 56.4% Inferential: 43.5% Critical: 0% |
| 7. | Figueroa Romero et al., 2016 | Perú | Determine the level of reading comprehension | 126 from the 1°year University/43% men and 57% women/15–26 years | Reading comprehension test 10 fragments with 28 questions | Bibliographic datasheet | Literal: 86.7% Inferential: 45.4% Critical: 34.29% |

from university degrees in social sciences, such as psychology and education (71.42%) followed by health sciences (14.28%) engineering and a publication (14.28%) that does not indicate origin. These publications selected according to the inclusion criteria for the meta-analysis come from more countries with a variety of educational systems, but all from South America. Specifically, the countries that have more studies are Mexico (28.57%) and Colombia, Chile, Bolivia, Peru, and Ecuador with 14.28% each, respectively. The years in which they were published are 2.57% in 2018 and 2016 and 14.28% in 2019, 2014, and 2013.

A total of 57% of the studies analyze four levels of reading comprehension (literal, inferential, critical, and organizational) and 43% investigate three levels of reading comprehension (literal, inferential, and critical). Based on the moderating variables, 57% of the studies use standardized reading comprehension measures and 43% non-standardized measures. According to the evaluation test used, 29% use multiple-choice questions and 71% combine multiple-choice questions plus open questions. 43% use an argumentative text and 57% other types of texts (not indicated in studies). By type of career, 71% are students of social sciences and 29% of other different careers, such as engineering or health sciences. In addition, 71% are articles and 29% with research works (thesis and degree works).

**Table 2** shows the reading comprehension assessment instruments used by the authors of the empirical research integrated into the meta-analysis.

## Meta-Analytic Analysis of the Level of Reading Comprehension

The literal level presents a mean proportion effect size of 56% (95% CI = 39–72%; **Figure 2**). The variability between the different samples of the literal level of reading comprehension was significant ($Q = 162.066$, $p < 0.001$; $I^2 = 96.3\%$). No moderating variable used in this research had a significant contribution to heterogeneity: type of measurement ($p = 0.520$), type of test ($p = 0.114$), type of text ($p = 0.520$), type of career ($p = 0.235$), and type of publication ($p = 0.585$). The high variability is explained by other factors not considered

**TABLE 2** | Reading comprehension assessment tests used in higher education.

| Studies | Evaluation tests | Description | Validation/Baremation |
|---|---|---|---|
| Del Pino-Yépez et al., 2019 | *Ad hoc* text with 12 questions | Text "Narcissism" with 12 questions: 4 literal, 4 inferential, and 4 critical. 40 min | Validation: no Reliability: no Baremation: no |
| Guevara Benítez et al., 2014; Márquez et al., 2016; Sanabria Mantilla, 2018 | Instrument to measure reading comprehension in university students (ICLAU) | 965-word text on "Evolution and its history." Then 7 questions are answered as: 2 literal, 2 inferential, 1 organizational, 1 critical, and 1 appreciative. 1 h | Inter-judge validation Reliability: no Baremation: no |
| Sáez Sánchez, 2018 | *Ad hoc* text with questions | 596-word text on "Ausubel's theory." Then literal, inferential, organizational, appreciative, and critical level questions | Validation: no Reliability: no Baremation: no |
| Yáñez Botello, 2013 | Arenas Reading Comprehension Assessment Questionnaire (2007) | Texts 4: 2 literary and 2 scientific with 32 questions each and four answer options | Inter-judge validation Reliability: no Baremation: no |
| Figueroa Romero et al., 2016 | Reading comprehension test by Violeta Tapia Mendieta and Maritza Silva Alejos | 35 min | Validation: empirical validity: 0.58 Reliability: test-retest: 0.53 Baremation: yes |

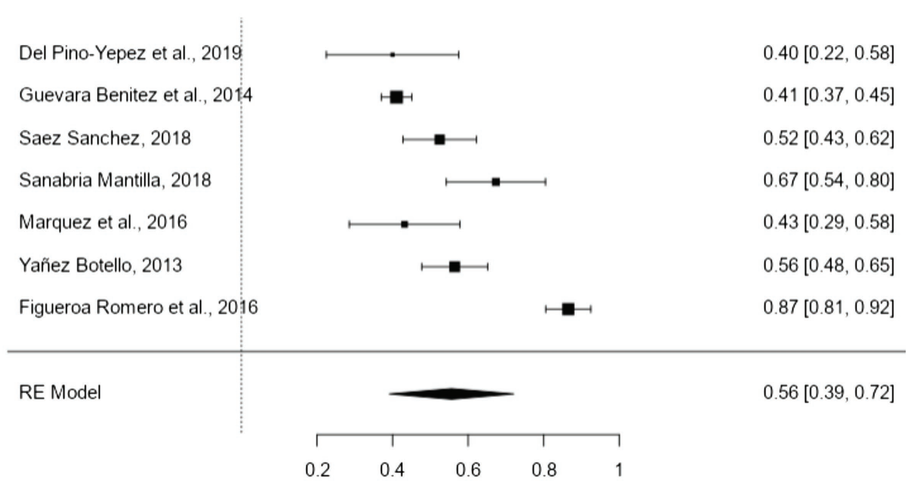


**FIGURE 2** | Forest plot of literal level.

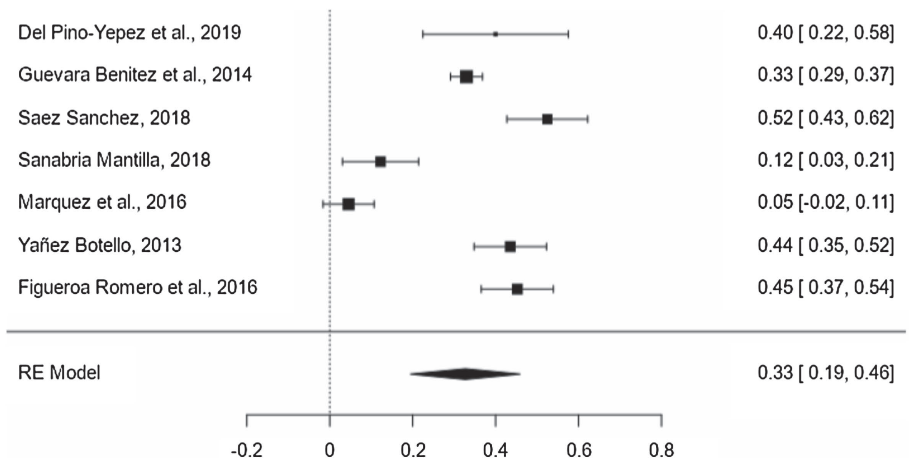


**FIGURE 3 |** Forest plot of inferential level.

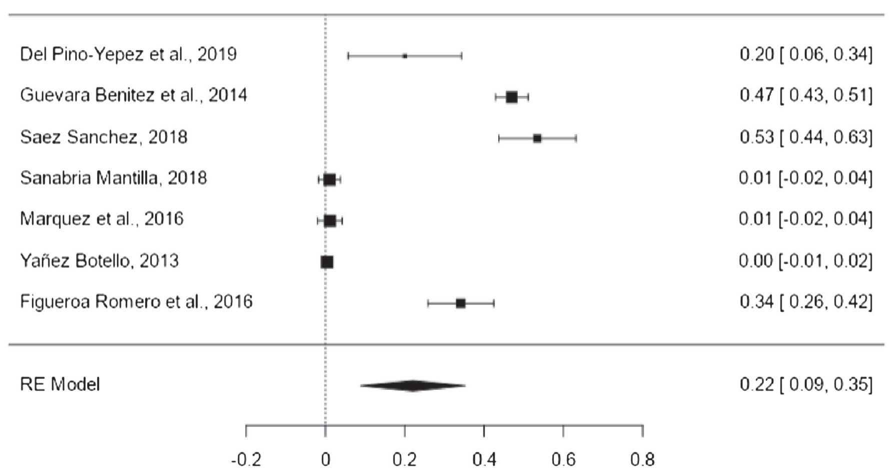


**FIGURE 4 |** Forest plot of critical level.

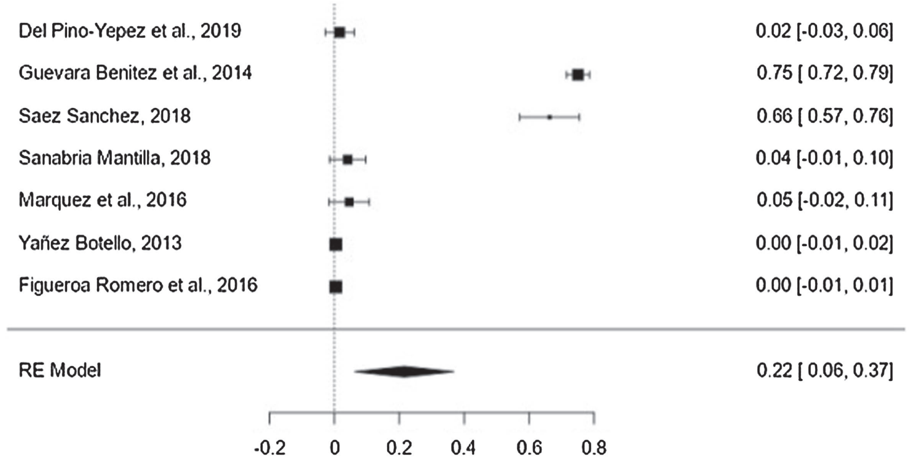


**FIGURE 5 |** Forest plot of organizational level.

**TABLE 3** | Results of effect size comparison.

| | $X^2$ | Difference | CI | Value of *p* |
|---|---|---|---|---|
| Literal-Inferential | 110.963 | 22.9% | 18.7035–26.9796% | $p < 0.0001$ |
| Literal-Critical | 248.061 | 33.6% | 25.5998–37.4372% | $p < 0.0001$ |
| Literal-Organizational | 264.320 | 34.6% | 30.6246–38.4088% | $p < 0.0001$ |
| Inferential-Critical | 30.063 | 10.7% | 6.865–14.4727% | $p < 0.0001$ |
| Inferential-Organizational | 36.364 | 11.7% | 7.9125–15.4438% | $p < 0.0001$ |
| Critical-Organizational | 0.309 | 1% | −2.5251–4.5224% | $p = 0.5782$ |

**TABLE 4** | Publication bias results.

| | Fail-safe N | Value of *p* | Regression test | Value of *p* |
|---|---|---|---|---|
| Literal | 3115.000 | <0.001 | −0.571 | 0.568 |
| Inferential | 1145.000 | <0.001 | 0.687 | 0.492 |
| Critical | 783.000 | <0.001 | 1.862 | 0.063 |
| Organizational | 1350.000 | <0.001 | 1.948 | 0.051 |

in this work, such as the characteristics of the students (cognitive abilities) or other issues.

The inferential level presents a mean proportion effect size of 33% (95% CI = 19–46%; **Figure 3**). The variability between the different samples of the inferential level of reading comprehension was significant ($Q = 125.123$, $p < 0.001$; $I^2 = 95.2\%$). The type of measure ($p = 0.011$) and the type of text ($p = 0.011$) had a significant contribution to heterogeneity. The rest of the variables had no significance: type of test ($p = 0.214$), type of career ($p = 0.449$), and type of publication ($p = 0.218$). According to the type of measure, the proportion of students who have an optimal level in inferential administering a standardized test is 28.7% less than when a non-standardized test is administered. The type of measure reduces variability by 2.57% and explains the differences between the results of the studies at the inferential level. According to the type of text, the proportion of students who have an optimal level in inferential using an argumentative text is 28.7% less than when using another type of text. The type of text reduces the variability by 2.57% and explains the differences between the results of the studies at the inferential level.

The critical level has a mean effect size of the proportion of 22% (95% CI = 9–35%; **Figure 4**). The variability between the different samples of the critical level of reading comprehension was significant ($Q = 627.044$, $p < 0.001$; $I^2 = 99.04\%$). No moderating variable used in this research had a significant contribution to heterogeneity: type of measurement ($p = 0.575$), type of test ($p = 0.691$), type of text ($p = 0.575$), type of career ($p = 0.699$), and type of publication ($p = 0.293$). The high variability is explained by other factors not considered in this work, such as the characteristics of the students (cognitive abilities).

The organizational level presents a mean effect size of the proportion of 22% (95% CI = 6–37%; **Figure 5**). The variability between the different samples of the organizational level of reading comprehension was significant ($Q = 1799.366$, $p < 0.001$; $I^2 = 99.67\%$). The type of test made a significant contribution to heterogeneity ($p = 0.289$). The other moderating variables were not significant in this research: type of measurement ($p = 0.289$), type of text ($p = 0.289$), type of career ($p = 0.361$), and type of publication ($p = 0.371$). Depending on the type of test, the proportion of students who have an optimal level in organizational with multiple-choices tests plus open questions is 37% higher than while using only multiple-choice tests. The type of text reduces the variability by 0.27% and explains the differences between the results of the studies at the organizational level.

**Table 3** shows the difference between the estimated effect sizes and the significance. There is a larger proportion of students having an optimal level of reading comprehension at the literal level compared to the inferential, critical, and organizational level; an optimal level of reading comprehension at the inferential level vs. the critical and organizational level.

## Analysis of Publication Bias

This research uses two ways to verify the existence of bias independently of the sample size. **Table 4** shows the results and there is no publication bias at any level of reading comprehension.

# DISCUSSION

This research used a systematic literature search and meta-analysis to provide estimates of the number of cases of university students who have an optimal level in the different levels of reading comprehension. All the information available on the subject at the international level was analyzed using international databases in English and Spanish, but the potentially relevant publications were limited. Only seven Spanish language studies were identified internationally. In these seven studies, the optimal performance at each level of reading comprehension varied, finding heterogeneity associated with the very high estimates, which indicates that the summary estimates have to be interpreted with caution and in the context of the sample and the variables used in this meta-analysis.

In this research, the effects of the type of measure, type of test, type of text, type of career, and type of publication have been analyzed. Due to the limited information in the publications, it was not possible to assess the effect of any more moderating variables.

We found that some factors significantly influence heterogeneity according to the level of reading comprehension considered. The type of measure influenced the optimal performance of students in the inferential level of reading comprehension; specifically, the proportion of students who have an optimal level in inferential worsens if the test is standardized. Several studies (Pike, 1996; Koretz, 2002) identify differences between standardized and non-standardized measures in reading comprehension and a favor of non-standardized measures developed by the researchers (Pyle et al., 2017). The ability to generate inferences of each individual may difficult to standardize because each person differently identifies the relationship between the parts of the text and integrates it with their previous knowledge (Oakhill, 1982; Cain et al., 2004). This mental representation of the meaning of the text is necessary to create a model of the situation and a deep understanding (McNamara and Magliano, 2009; van den Broek and Espin, 2012).

The type of test was significant for the organizational level of reading comprehension. The proportion of students who have an optimal level in organizational improves if the reading comprehension assessment test is multiple-choice plus open questions. The organizational level requires the reordering of written information through analysis and synthesis processes (Guevara Benítez et al., 2014); therefore, it constitutes a production task that is better reflected in open questions than in reproduction questions as multiple choice (Dinsmore and Alexander, 2015). McNamara and Kintsch (1996) identify that open tasks require an effort to make inferences related to previous knowledge and multidisciplinary knowledge. Important is to indicate that different evaluation test formats can measure different aspects of reading comprehension (Zheng et al., 2007).

The type of text significantly influenced the inferential level of reading comprehension. The proportion of students who have an optimal level in inferential decreases with an argumentative text. The expectations created before an argumentative text made it difficult to generate inferences and, therefore, the construction of the meaning of the text. This result is in the opposite direction to the study by Diakidoy et al. (2011) who find that the refutation text, such as the argumentative one, facilitates the elaboration of inferences compared to other types of texts. It is possible that the argumentative text, given its dialogical nature of arguments and counterarguments, with a subject unknown by the students, has determined the decrease of inferences based on their scarce previous knowledge of the subject, needing help to elaborate the structure of the text read (Reznitskaya et al., 2007). It should be pointed out that in meta-analysis studies, 43% use argumentative texts. Knowing the type of the text is relevant for generating inferences, for instance, according to Baretta et al. (2009) the different types of text are processed differently in the brain generating more or fewer inferences; specifically, using the N400 component, they find that expository texts generate more inferences from the text read.

For the type of career and the type of publication, no significance was found at any level of reading comprehension in this sample. This seems to indicate that university students have the same level of performance in tasks of literal, critical inferential, and organizational understanding regardless of whether they are studying social sciences, health sciences, or engineering. Nor does the type of publication affect the state of the different levels of reading comprehension in higher education.

The remaining high heterogeneity at all levels of reading comprehension was not captured in this review, indicating that there are other factors, such as student characteristics, gender, or other issues, that are moderating and explaining the variability at the literal, inferential, critical, and organizational reading comprehension in university students.

To the comparison between the different levels of reading comprehension, the literal level has a significantly higher proportion of students with an optimal level than the inferential, critical, and organizational levels. The inferential level has a significantly higher proportion of students with an optimal level than the critical and organizational levels. This corresponds with data from other investigations (Márquez et al., 2016; Del Pino-Yépez et al., 2019) that indicate that the literal level is where university students execute with more successes, being more difficult and with less success at the inferential, organizational, and critical levels. This indicates that university students of this sample do not generate a coherent situation model that provides them with a global mental representation of the read text according to the model of Kintsch (1998), but rather they make a literal analysis of the explicit content of the read text. This level of understanding can lead to less desirable results in educational terms (Dinsmore and Alexander, 2015).

The educational implications of this meta-analysis in this sample are aimed at making universities aware of the state of reading comprehension levels possessed by university students and designing strategies (courses and workshops) to optimize it by improving the training and employability of students. Some proposals can be directed to the use of reflection tasks, integration of information, graphic organizers, evaluation, interpretation, nor the use of paraphrasing (Rahmani, 2011). Some studies (Hong-Nam and Leavell, 2011; Parr and Woloshyn, 2013) demonstrate the effectiveness of instructional courses in improving performance in reading comprehension and metacognitive strategies. In addition, it is necessary to design reading comprehension assessment tests in higher education that are balanced, validated, and reliable, allowing to have data for the different levels of reading comprehension.

## LIMITATIONS AND CONCLUSION

This meta-analysis can be used as a starting point to report on reading comprehension levels in higher education, but the results should be interpreted with caution and in the context of the study sample and variables. Publications without sufficient data and inaccessible articles, with a sample of seven studies, may have limited the international perspective. The interest in studying reading comprehension in the mother tongue, using only unimodal texts, without the influence of technology and with English and Spanish has also limited the review. The limited amount of data in the studies has limited meta-regression.

This review is a guide to direct future research, broadening the study focus on the level of reading comprehension using digital technology, experimental designs, second languages, and investigations that relate reading comprehension with other factors (gender, cognitive abilities, etc.) that can explain the heterogeneity in the different levels of reading comprehension. The possibility of developing a comprehensive reading comprehension assessment test in higher education could also be explored.

This review contributes to the scientific literature in several ways. In the first place, this meta-analytic review is the only one that analyzes the proportion of university students who have an optimal performance in the different levels of reading comprehension. This review is made with international publications and this topic is mostly investigated in Latin America. Second, optimal performance can be improved at all levels of reading comprehension, fundamentally inferential, critical, and organizational. The literal level is significantly the level of reading comprehension with the highest proportion of optimal performance in university students. Third, the students in this sample have optimal performance at the inferential level when they are non-argumentative texts and non-standardized measures, and, in the analyzed works, there is optimal performance at the organizational level when multiple-choice questions plus open questions are used.

The current research is linked to the research project "Study of reading comprehension in higher education" of Asociación Educar para el Desarrollo Humano from Argentina.

## DATA AVAILABILITY STATEMENT

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

## AUTHOR CONTRIBUTIONS

Cd-l-P had the idea for the article and analyzed the data. ML-R searched the data. Cd-l-P and ML-R selected the data and contributed to the valuable comments and manuscript writing. All authors contributed to the article and approved the submitted version.

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# Teachers' Knowledge and Use of Evidenced-Based Practices for Students With Autism Spectrum Disorder in Saudi Arabia

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The evidenced-based practices (EBPs) movement in the field of special education began ~20 years ago. This study contributes to that literature. It investigates the teachers' knowledge and use of EBPs to teach students with autism spectrum disorder (ASD) in Saudi Arabia. The Teachers' Knowledge and Use of EBPs Survey was administered to 240 special education teachers. The participants generally reported a medium level of knowledge and use of EBPs for students with ASD. Female teachers' use of EBPs was greater than that of males, and teachers who attended more than five professional development programs reported greater use of EBPs than those that attended fewer programs. Knowledge and use of EBPs were related. Gender and professional development programs were predictors of teachers' use of EBPs for students with ASD. Teachers' knowledge of EBPs for students with ASD is a vital indicator of teachers' use of those practices, professional development programs can improve such knowledge and use, and teachers' use of EBPs for students with ASD could be improved by offering high-quality professional development programs.

**Keywords: autism spectrum disorder, evidenced-based practices, knowledge, use, teachers, Saudi Arabia**

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## INTRODUCTION

Autism spectrum disorder (ASD) is defined as a neurodevelopmental disorder characterized by persistent deficits in social communication and interactions and displays of restricted repetitive behaviors, interests, or activities (American Psychiatric Association, 2013; Kakkar, 2019). These symptoms appear during early childhood and impair everyday functioning (American Psychiatric Association, 2013; Wadhera et al., 2021). ASD is one of the most common neurodevelopmental disorders that affect children (Leblanc et al., 2009), and there has been an increase in the number of individuals diagnosed with the condition (Leblanc et al., 2009; Stansberry-Brusnahan and Collet-Klingenberg, 2010; Odom et al., 2013; Wong et al., 2015). According to Maenner et al. (2020), ~1 in 54 children were identified to have ASD in the United States (US), a rate higher than the 1 in 150 children in 2000–2002. In addition, the estimates of the prevalence of ASD have approached 1% of the population in the US and that in all other countries, with similar results in child and adult samples (American Psychiatric Association, 2013). Many of these children with ADS are included in general education classrooms (Meindl et al., 2020).

The increased prevalence of ASD and the inclusion of students with ASD in general education classrooms (Meindl et al., 2020) have intensified the need for effective practices that can significantly affect the social and educational functioning of these students. Unfortunately, there is no cure for ASD (Wadhera and Kakkar, 2020) and no single intervention has been recommended universally (Stansberry-Brusnahan and Collet-Klingenberg, 2010). Thus, teaching students with ASD can be a difficult task, and fulfilling their needs is challenging for teachers (Hsiao and Sorensen Petersen, 2019) because many of the symptoms associated with ASD can adversely affect these students' learning abilities (Leblanc et al., 2009).

The research has emphasized using evidence-based practices (EBPs; Odom et al., 2013; Wong et al., 2015) to meet the significant needs of students with ASD in inclusive classrooms (Marder and deBettencourt, 2015). Research has indicated that a teacher's use of EBPs can significantly improve the outcomes of students with ASD and the lives of their families (Cook and Odom, 2013; Alexander et al., 2015; Marder and deBettencourt, 2015). In addition, legal requirements (e.g., the Individuals with Disabilities Education Improvement Act, 2004 and the Every Student Succeeds Act, 2015) require teachers to use EBPs to fulfill the needs of students with disabilities (Lauderdale-Littin and Brennan, 2018; Spooner et al., 2019). This effort has resulted in EBPs being a common term in special education (Cook et al., 2012). EPBs are defined as teaching programs, instructional strategies, or interventions supported by experimental research and professional wisdom that result in consistent positive outcomes in students (Burns and Ysseldyke, 2009; Marder and deBettencourt, 2015; Beam and Mueller, 2017). However, research has revealed that non-EBPs are being used by professionals in the field of special education despite an increase in the number of EBPs (Hess et al., 2008; Paynter and Keen, 2015). Notably, special education specialists have reported using ineffective instructional practices more often than some research-based practices (Cook and Odom, 2013).

Researchers have measured teachers' perceived frequency of using EBPs with students with disabilities in North America (Burns and Ysseldyke, 2009), Australia (Carter et al., 2011), and the Czech Republic (Carter et al., 2012) and reported the extensive use of EBPs such as direct instruction and applied behavior analysis. Notably, some non-EBPs (e.g., modality instruction) were commonly used, and applied behavior analysis had been used with similar frequency (Burns and Ysseldyke, 2009; Carter et al., 2011, 2012). Unfortunately, non-EBPs were frequently used in special schools and classrooms more than regular classrooms (Carter et al., 2012). Czech teachers used EBPs at a higher level than US and Australian teachers (Burns and Ysseldyke, 2009; Carter et al., 2011, 2012). However, these studies did not focus on a particular category of special education.

Other studies (Hess et al., 2008; Paynter and Keen, 2015; Paynter et al., 2017; Knight et al., 2019) have focused on ASD. In a survey study, less than 8% of teachers who taught children with ASD from preschool to twelfth grade were using EBPs, and several of the top-reported strategies used in the classroom were non-EBPs (Hess et al., 2008). Special education teachers of students with autism and/or intellectual disability reported daily use of a wide range of EBPs. Notably, some ineffective or harmful practices were used more frequently than EBPs were. Participants who received any type of training or resources related to the practice in the last year indicated significantly more use of that practice than those who did not receive any type of training or resources (Knight et al., 2019).

Professionals and paraprofessionals' knowledge and use of EBPs were explored in autism early intervention services in Australia. They had a higher level of knowledge and use of EBPs than of non-EBPs (Paynter and Keen, 2015; Paynter et al., 2017). However, professionals reported higher levels of knowledge (Paynter and Keen, 2015; Paynter et al., 2017) and use (Paynter and Keen, 2015) of EBPs than paraprofessionals did. There was a significant association between the knowledge and use of EBPs, with knowledge level significantly predicting the use of EBPs (Paynter and Keen, 2015; Paynter et al., 2017).

In Saudi Arabia, research indicated that teachers reported low use of peer-mediated and self-mediated interventions. Female teachers were more knowledgeable about EBPs than male teachers. Major, educational level, and years of teaching experience were not significantly related to their knowledge of EBPs. However, there was a strong positive relationship between knowledge and use of EBTPs (Alhossein, 2016).

Teachers require adequate knowledge of EBPs and the skills necessary to implement them with their students (Marder and deBettencourt, 2015). Researchers have suggested several rationales for using EBPs with students with ASD, for example, the increasing number of students with ASD in schools, risks associated with disappointing outcomes for students with ASD and their families, and the history of non-EBPs that have been offered to the public (Marder and deBettencourt, 2015). Almost two decades have passed since the beginning of the EBP movement in the field of special education. The literature review revealed several evaluations of teachers' knowledge and use of EBPs in developed countries (e.g., the US and Australia). The results in the literature have highlighted many topics related to knowing and using EBPs in those countries. However, the literature review revealed that no study has investigated teachers' knowledge and use of EBPs for students with ASD in developing countries. Thus, such a study would add to the literature by providing information on how teachers perceive their knowledge and use of EBPs in those countries. These insights will assist in identifying areas for further training and investigating generalization beyond developed countries. Therefore, this study was conducted to investigate the knowledge and use of EBPs to teach students with ASD by teachers in Saudi Arabia. This study attempted to answer four research questions: (i) to what extent do teachers know and use EBPs with students with ASD, (ii) to what extent do teachers differ in their reported knowledge and use of EBPs, (iii) what is the relationship between reported knowledge and use of EBPs, and (iv) what factors influence teachers' use of EBPs.

# MATERIALS AND METHODS

## Participants

Participants were selected using probability sampling method with random sampling technique. They included 240 special education teachers in the city of Riyadh, Saudi Arabia. In this study, female and male teachers participated. Female teachers

**TABLE 1 |** Participants' characteristics.

| Variables | % |
|---|---|
| **Gender** | |
| Male | 47.7 |
| Female | 53.3 |
| **Years of teaching experience with children with autism spectrum disorder** | |
| <5 years | 50.8 |
| Between 5 and 10 years | 44.2 |
| More than 10 years | 5 |
| **Highest degree earned** | |
| Bachelor | 95 |
| Master and above | 5 |
| **Professional development programs** | |
| None | 9.2 |
| 2 programs or fewer | 23.8 |
| From 3 to 5 programs | 33.3 |
| More than 5 programs | 33.8 |

represented 53.3% of respondents and the remaining were male teachers. Most of the participants (72%) had majored in autism education, and the others were special education majors (24%) or general education majors with some professional development programs in special education (9%). The participants' experience with teaching students with autism ranged from <5 years to more than 10 years. Most of the participants, 94% and 95%, respectively, reported that they had <10 years of teaching experience or a bachelor's degree, and 5% reported that they had a master's degree. As for professional development programs, almost 9% of participants had not attended any training programs on autism, and the others had attended from two to more than five of some types of training programs. **Table 1** presents the demographic information of the participants.

## Instrument

The author developed the Teachers Knowledge and Use of EPBs Survey on the basis of a literature review (e.g., Paynter and Keen, 2015; Wong et al., 2015; Paynter et al., 2017). The survey comprised two parts. The first part of the survey collected demographic information: gender, major, highest degree earned (bachelor's degree, master's degree), overall years of teaching experience of students with ASD, and number of professional development programs attended. The second part of the survey contained a list of EBPs for teachers of students with ASD in educational settings and 26 items with forced-choice responses. The list was created by using the EPBs for children, youth, and young adults report developed by Wong et al. (2015). On the survey, each item included the name of the practice and its definition. The teachers read each item, identified their knowledge and use of it, and rated their knowledge and use of each practice on a 4-point scale from 0 = I don't know/never used to 3 = high knowledge/used frequently. The higher the score, the greater the knowledge and use of EBPs. The duration of the survey was ∼10–15 min. Once the survey items were initially developed, several expert faculty members in the field of autism provided feedback on the clarity of the items and the constructs of the survey. They indicated that the survey was appropriate for the research purpose. In addition, the coefficient alphas for knowledge and use of EBPs were calculated separately. They demonstrated high reliability, with estimates of 0.93 for knowledge and 0.935 for use. These results indicated that the survey could be used as a valid, reliable tool for assessing the knowledge and use of EBPs for students with ASD.

## Procedures

The institutional review board (IRB) review was approved by the IRB committee in the school district, to ensure this study's compliance and ethical conduct of research involving human participants. After receiving IRB approval, public schools and private centers that provide services for ASD in Riyadh, Saudi Arabia, were identified. The two eligibility criteria for the participants were as follows: teachers in a public school or private center in Riyadh that provide services for students with ASD and who were teaching students with ASD at the time of the invitation to participate in the study. A coordinator at each site was contacted to introduce the purpose of the study, which included a brief description of the study, an informed consent form, demographic information, and the survey. The coordinators were further asked to distribute and collect the surveys. Participants were told that they were free to withdraw from the study at any point with no penalty. Two weeks later, follow-up reminders were sent to remind the coordinators to collect the surveys, which were then collected by the researcher.

## Data Analysis

Statistical Package of Social Science for Windows Version 22 was used to analyze the data. Preliminary analyses were conducted to determine whether the data was normally distributed using a variety of methods (Normal Q-Q Plots, histograms, and Shapiro-Wilk test). The results indicated that the data approximately normally distributed. In addition, there was homogeneity of variances, as assessed by Levene's test for equality of variances. Descriptive statistics (i.e., mean and standard deviations) were used to answer the first research question that measured teachers' knowledge and use of EBPs for students with ASD. Two independent sample $t$-tests and ANOVA were conducted to examine the differences in reported knowledge and use of EBPs on the basis of gender, teaching experience with students with ASD, and whether special education teachers had attended professional development programs. To measure the correlations between reported use of EBPs and teachers' knowledge of EBPs, Pearson's product-moment correlation coefficient was calculated. In addition, a stepwise multiple regression was used to test the predictability of several factors (gender, teaching experience of students with ASD, and professional development programs) for the teachers' use of EBPs.

# RESULTS

## Teachers' Knowledge and Use of EBPs

**Table 2** presents the teachers' mean scores of their perceived knowledge and self-reported use of each EBP and the overall means for knowledge and use of EBPs. The results indicated that the total mean for knowledge was 2.33, with item means ranging from 2.06 to 2.71. As for use, the total mean was 2.07, with item means ranging from 1.69 to 2.66. Generally, participants reported medium knowledge and use of EBPs for students with ASD. They agreed that the most commonly known and used EPBs were reinforcement ($M = 2.71$ for knowledge, $M = 2.66$ for use), prompting ($M = 2.70$ for knowledge, $M = 2.62$ for use), extinction ($M = 2.61$ for knowledge, $M = 2.42$ for use), and modeling ($M = 2.55$ for knowledge, $M = 2.40$ for use). However, there was variability in the least-known and least-used EPBs. Pivotal response training ($M = 2.06$), time delay ($M = 2.07$), scripting ($M = 2.07$), functional communication training ($M = 2.12$), and self-management ($M = 2.17$) were the least-known EPBs. The least-used EPBs were scripting ($M = 2.69$), social narratives ($M = 2.70$), self-management ($M = 2.77$), time delay ($M = 2.82$), and video modeling ($M = 2.82$).

## Demographic Comparisons of Teachers

### Gender

Saudi Arabia uses a single-education system: boys are educated by male teachers and girls are educated by female teachers. Thus, teachers' responses were compared based on their gender. An independent-samples *t*-test was conducted to evaluate that gender would be related to the teachers' reported knowledge and use of EBPs. Female teachers reported more knowledge of EBPs ($M = 2.44$, $SD = 0.411$) than male teachers did ($M = 2.20$, $SD = 0.495$), $t\ (238) = -3.998$, $p = 0.000$, $d = 0.473$. Female teachers also reported more use of EBPs ($M = 2.24$, SD = 0.453) than male teachers did ($M = 1.88$, SD = 0.554), $t(238) = -5.549$, $p = 0.000$, $d = 0.652$.

### Teaching Experience

In this study, teachers were compared based on their experience with teaching students with ASD. They were placed into three groups (<5 years, from 5 to 10 years, more than 10 years). To determine whether the teaching experience would be related to the teachers' reported knowledge and use of EBPs, one-way ANOVA was conducted. Comparisons across teaching experience groups revealed no significant differences in reported knowledge of EBPs, [$F_{(2,237)} = 2.31$, $p = 0.101$, $\eta p2 = 0.019$]. The teachers were significantly different in reporting their use of EBPs, [$F_{(2,237)} = 3.225$, $p = 0.042$, $\eta p2 = 0.026$]. The Tukey honestly significant difference (HSD) test revealed that teachers with more than 10 years' experience in teaching reported more use of EBPs ($M = 2.45$, $SD = 0.435$) than did teachers with <5 years' experience ($M = 2.06$, $SD = 0.496$), $p = 0.040$, and teachers with between 5 and 10 years' experience ($M = 2.05$, $SD = 0.571$), $p = 0.035$. No significant differences were found between teachers with <5 years' experience and teachers with between 5 and 10 years' experience, $p = 0.984$.

### Professional Development Programs

Teachers were divided into four groups: never attended professional development programs on teaching students with ASD, attended fewer than two programs, attended three to five programs, and attended more than five programs. To determine whether the professional development programs would be related to the teachers' reported knowledge and use of EBPs, one-way ANOVA was conducted. Comparisons across numbers of professional development programs attended revealed significant differences in reported knowledge of EBPs, [$F_{(3,236)} = 12.919$, $p = 0.000$, $\eta p2 = 0.141$]. *Post-hoc* comparisons using Tukey HSD indicated that teachers who attended more than five programs reported knowing EBPs ($M = 2.56$, $SD = 0.379$) more than teachers who never attended professional development programs ($M = 2.05$, $SD = 0.466$), $p = 0.000$, teachers who attended fewer than two programs ($M = 2.18$, $SD = 0.475$), $p = 0.000$, and teachers who attended three to five programs ($M = 2.28$, $SD = 0.450$), $p = 0.000$. Other comparisons revealed no significant differences among teachers.

In addition, a significant difference was found in reported use of EBPs, [$F_{(3,236)} = 16.785$, $p = 0.000$, $\eta p2 = 0.176$]. *Post-hoc* comparisons using Tukey HSD indicated that teachers who attended more than five programs reported using EBPs ($M = 2.37$, SD = 0.467) more than teachers who never attended any programs ($M = 1.80$, SD = 0.492), p = 0.000, teachers who attended fewer than two programs ($M = 1.87$, SD = 0.513), p = 0.000, and teachers who attended three to five programs ($M = 1.99$, SD = 0.488), p = 0.000. Other comparisons revealed no significant differences among participants.

## Correlations Between Knowledge and Use of EBPs

Knowledge of EBPs was significantly correlated with the reported use of EBPs ($p = 0.000$). The strength of these correlations was large ($r = 0.859$). Thus, a high level of knowledge of EBPs could lead to high use of them.

## Factors Related to Teachers' Use of EBPs

Stepwise multiple regression was used to evaluate factors related to the use of EPBs. The predictors were gender, total years of experience teaching students with ASD, and total number of professional development programs on teaching students with ASD attended. In **Table 3**, the total number of professional development programs attended was entered into the regression equation in Step 1 of the analysis and was significantly related to the use of EBPs, [$F_{(1,238)} = 42.143$, $p < 0.000$]. In Step 2, the gender variable was added to the model and there was a significant change ($p = 0.000$), and $R^2$ increased to 0.235. The total years of experience teaching students with ASD variable was excluded because it did not add to the predictability of the model. This result indicated that combination the of the total number of professional development programs attended and gender were the best predictors of EBPs' use. However, the use of EBPs was not affected by the total years of experience teaching students with ASD variables.

**TABLE 2 |** Mean Scores (M) and Standard Deviation (SD) of knowledge and use of evidence-based practices.

| Evidence-based practices | Knowledge | | Use | |
|---|---|---|---|---|
| | M | SD | M | SD |
| Antecedent-based intervention | 2.25 | 0.745 | 1.99 | 0.816 |
| Cognitive behavioral intervention | 2.18 | 0.771 | 2.00 | 0.790 |
| Differential reinforcement of alternative, incompatible, or other behavior | 2.41 | 0.743 | 2.28 | 0.803 |
| Discrete trial teaching | 2.21 | 0.842 | 2.02 | 0.915 |
| Exercise | 2.35 | 0.740 | 2.05 | 0.844 |
| Extinction | 2.61 | 0.553 | 2.42 | 0.601 |
| Functional behavior assessment | 2.22 | 0.780 | 1.98 | 0.896 |
| Functional communication training | 2.12 | 0.840 | 1.87 | 0.960 |
| Modeling | 2.55 | 0.689 | 2.40 | 0.748 |
| Naturalistic intervention | 2.22 | 0.861 | 2.03 | 0.924 |
| Peer-mediated instruction and intervention | 2.38 | 0.744 | 1.95 | 0.932 |
| Picture exchange communication system | 2.41 | 0.743 | 2.09 | 0.935 |
| Pivotal response training | 2.06 | 0.904 | 1.87 | 1.004 |
| Prompting | 2.70 | 0.525 | 2.62 | 0.551 |
| Reinforcement | 2.71 | 0.508 | 2.66 | 0.540 |
| Response interruption/redirection | 2.43 | 0.705 | 2.25 | 0.780 |
| Scripting | 2.07 | 0.891 | 1.69 | 0.944 |
| Self-management | 2.17 | 0.823 | 1.77 | 0.986 |
| Social narratives | 2.20 | 0.836 | 1.70 | 0.956 |
| Social skills training | 2.33 | 0.763 | 2.08 | 0.902 |
| Structured play group | 2.24 | 0.822 | 1.88 | 0.933 |
| Task analysis | 2.45 | 0.701 | 2.27 | 0.832 |
| Technology-aided instruction and intervention | 2.37 | 0.748 | 2.10 | 0.860 |
| Time delay | 2.07 | 0.875 | 1.82 | 0.946 |
| Video modeling | 2.34 | 0.775 | 1.86 | 0.971 |
| Visual support | 2.48 | 0.702 | 2.24 | 0.853 |
| Total | 2.33 | 0.467 | 2.07 | 0.533 |

**TABLE 3 |** Stepwise regression analysis of gender, total years of teaching experience, and total number of professional development programs attended on use of evidence-based practices ($N = 240$).

| Variable | *B* | *SE B* | β |
|---|---|---|---|
| **Step 1** | | | |
| Constant | 1.449 | | |
| Total number of professional development programs attended | 0.214** | 0.033 | 0.388 |
| Adjusted $R^2$ | 0.147 | | |
| *F* | 42.143** | | |
| **Step 2** | | | |
| Constant | 1.028 | | |
| Total number of professional development programs attended | 0.193** | 0.032 | 0.351 |
| Gender | 0.314** | 0.061 | 0.294 |
| Adjusted $R^2$ | 0.229 | | |
| *F* | 36.485** | | |
| $\Delta R^2$ | 0.085 | | |
| F-change | 26.340** | | |

*$^{**}p < 0.01$; B, unstandardized regression coefficient; SE, standard error; ß, standardized regression coefficient; $\Delta R^2$, difference in the proportion of variance explained.*

## DISCUSSION

This study examined the levels of perceived knowledge and self-reported use of EBPs for students with ASD among special education teachers and the relationship between knowledge and use of EPBs. In addition, the group comparisons were conducted based on several variables (gender, total years of experience teaching students with ASD, and number of professional development programs attended). Factors related to teachers' use of EBPs (gender, total years of experience teaching children with ASD, and number of professional development programs attended) were also explored. The results of the study indicate that participants reported medium knowledge and use of EBPs for students with ASD. This finding revealed that participants have satisfactory levels of the theoretical and conceptual foundation of EPBs and the use of these practices. This finding might indicate that teachers receive information from pre- and in-service professional development programs on EPBs and that they translate this knowledge into practice at an adequate level. However, this is perceived knowledge and self-reported use. This means that teachers may think they know and use the practices but that they may not have accurate knowledge and actual use.

The findings from the teachers' responses to each EPB are consistent with those in the literature in that reinforcement (Paynter and Keen, 2015; Paynter et al., 2017) and modeling (Knight et al., 2019) were from the most known and used EPBs. However, the picture exchange communication system was not the most frequently used strategy, as indicated by the literature (Paynter and Keen, 2015; Paynter et al., 2017). The results confirm what has been found in the literature (Paynter and Keen, 2015; Paynter et al., 2017) in which self-management and time delay were the least-known and used EPBs. It appears that teachers know and use common practices. They also may prefer positive practices that are used easily and with a group of students. There may be more opportunity or need to use some practices (e.g., reinforcement) throughout the day. By contrast, teachers avoided some EBPs such as self-management, video modeling, scripting, and social narratives, which require time and energy to prepare and use inside the classroom. These practices might be more suitable for individual use than group interventions and be appropriately used less often in response to specific needs. Moreover, teachers reported less knowledge about functional communication training and pivotal response training (Paynter and Keen, 2015; Paynter et al., 2017; Knight et al., 2019) because these may not be popular and are rarely used in the classroom. The literature has suggested that teachers may not understand pivotal response training (Knight et al., 2019) and have difficulty using it (Stahmer et al., 2019).

When the teachers' responses were compared by gender, female teachers knew and used more of EBPs than their male counterparts did. Autism researchers have not compared teachers on the basis of this variable. However, this variable might be important in this research because females are educated and teach in separate schools. An explanation for this result could be that females have received more pre- and in-service professional development programs than males have; thus, females' knowledge has been increased and thus led to more use of these practices. Another explanation could be that female school principals encourage teachers to attend workshops and support using EBPs inside their schools. Males may depend in their teaching on guidance from experienced teachers or use common practices in their schools regardless of their effectiveness, and females prefer practices supported by scientific evidence. An alternative explanation might be that there are gender differences in self-perceptions or response styles rather than in actual knowledge or use of EBPs.

Participants were compared based on experience teaching students with ASD. The comparisons revealed that the teaching experience of students with ASD did not affect the reported knowledge of EBPs. By contrast, they affect reported use of EBPs, where teachers with more than 10 years' experience reported using more EBPs than did teachers with less experience. This finding could be logical in that experience may not increase a teacher's knowledge of EBPs because she may have received inadequate information on it. However, experience may help teachers use the practices because the more experienced teachers have attempted to implement many practices and may thus have gained confidence and skills in using practices, whereas teachers with less experience could have less confidence and fewer skills.

The number of professional development programs attended on teaching students with ASD influenced reported knowledge and use of EBPs. Teachers who attended more than five professional development programs were more knowledgeable and used more EBPs than teachers who attended fewer professional development programs. This finding emphasizes the importance of professional development programs in increasing teachers' knowledge and use of EBPs. When teachers attend more professional development programs, they know more about these practices and use them in their classes. Attending more programs will provide teachers opportunities to discuss their needs with other professionals and share their experiences in using these practices. This practice would facilitate the implementation of practices.

Knowledge of EBPs was significantly related to the reported use of EBPs. This finding suggests that when teachers have high levels of knowledge of EBPs, they use them more often. This finding is consistent with those in the literature (Cook et al., 2008; Paynter and Keen, 2015; Paynter et al., 2017; Hsiao and Sorensen Petersen, 2019). Research has suggested that teachers' knowledge influences the use of EBPs (Jones, 2009). This finding may suggest that teachers prefer to use familiar practices. By contrast, unfamiliar practices are rarely used regardless of the evidence supporting their use (Cook et al., 2008). In addition, knowledge might be a major barrier to the use of EBPs. For instance, some teachers may be confused between the meaning of best practice and EBPs. They may use practices that have not had strong evidence bases (Hornby et al., 2013). Ensuring teachers have sufficient knowledge related to teaching is vital for using that knowledge but does not guarantee that it will be used with fidelity (Scheeler et al., 2016).

As for the factors predicting teachers' use of EBPs, the combination of the number of professional development programs attended and gender were the best predictors, and the total years of experience teaching children with ASD variables did not predict the use of EBPs. This finding emphasizes the importance of in-service training programs because the results indicated that females attended more professional programs and had more knowledge and use of EBPs than males did. When teachers work with students, they may experience problems that entail attending training programs to find solutions. Subsequently, they attempt to use these solutions in their classroom.

The results of this study have implications. Because a strong positive relationship was observed between knowledge and use of EBPs, improving teachers' knowledge of EBPs for students with ASD could increase their use of that practice when teaching these students. Therefore, improving teachers' knowledge of EBPs for students with ASD is necessary. This practice might entail the inclusion of courses on EBPs in teacher education programs and how to use EBPs inside the classrooms. These courses should combine knowledge with opportunities to practice the knowledge and provide feedback and support on the implementation of EBPs. In addition, school principals and school district leaders should encourage and require teachers to attend professional development programs on EBPs. In this study, teachers needed to attend more than five professional development programs to influence their knowledge and use of EBPs. This finding may indicate the quality of the programs provided to teachers. Inferior programs may hinder the benefits. Notably, research revealed a scarcity of quality in-service training on EBPs for students with ASD (Alexander et al., 2015). When teachers attend high-quality programs, they might need to attend fewer programs to learn a lot about the practices and use them in their classrooms. This result may highlight the need for effective models of professional development programs. Research has indicated that most commonly used professional development approaches have little influence on teachers' knowledge and use of EBPs for students with ASD (Hornby et al., 2013; Brock et al., 2014). Evidence suggests that the most effective models of professional development programs, such as individualized coaching and mentoring, are not used widely in schools (Brock et al., 2014). Satisfactory professional development programs were consistently cited as successful facilitators of EBP use (Forman et al., 2009). Effective teacher training necessitates the inclusion of multiple approaches (Morrier et al., 2011). Using lectures and handouts alone to disseminate information on EBPs is often useless (Alexander et al., 2015). Didactic training could help spread information but may not lead to using that information (Morrier et al., 2011). Training teachers to use EBPs should advance beyond didactic instruction, to emphasize practicing EBPs inside the classroom and provide feedback on their implementation (Marder and deBettencourt, 2015). The programs should include hands-on activities and opportunities to practice and receive feedback from an expert coach or supervisor in the use of EBPs. Providing performance feedback is essential to effective implementation (Hall, 2015). Research has also indicated a need for follow-up training (Alexander et al., 2015) and ongoing support (Hornby et al., 2013; Hall, 2015) to increase the adoption of new practices and levels of implementation fidelity (Alexander et al., 2015) and to sustain the use of EBPs (Hornby et al., 2013; Hall, 2015). Training all teachers in a short time is difficult. Thus, school district leaders should develop handbooks and websites (Test et al., 2015) on EBPs with the appropriate information, for example, a description of each EBP, the steps and materials necessary for its implementation, and checklists to assess the fidelity of implementation. This effort will help reach teachers, regardless of location.

Although this study's results have revealed crucial findings on the knowledge and use of EBPs for students with ASD in Saudi Arabia, its limitations should be considered. First, the scope of this study was limited to a large city; thus, the results might not represent national findings. However, in the studied city, the teachers represent various backgrounds and cultures. Further research could conduct a national study that includes teachers from urban, suburban, and rural locations and subsequently compare their results with the results of this study. Further research could also investigate whether teachers working in different types of cities differ in their knowledge and use of EBPs or replicate this study and include participants from other fields such as occupational therapists and speech pathologists to explore if they differ in their knowledge and use of EPBs from the teachers in this study (Paynter et al., 2017).

Furthermore, this study used a survey to measure teachers' knowledge and use of EBPs for students with ASD. Thus, the results were self-reported, and teachers may have indicated that they had a higher level of knowledge and use EBPs than they did in practice; additionally, they may have inaccurate knowledge or use the practices with low fidelity. In addition, females reported more knowledge and use of EBPs than males did, and gender predicted teachers' use of EBPs. This finding highlights the need for further research that uses mixed-method research. Researchers could survey teachers on EPBs and observe teachers inside their classrooms to compare the self-reported results with actual use. They could also interview teachers to obtain in-depth information on their perceptions and use of EBPs.

Teachers' attitudes may play an important role in understanding EPBs. Personal views and attitudes may also strongly impact teachers' use of the practices (Jones, 2009; Paynter et al., 2017). Positive attitudes toward EBPs may facilitate high levels of knowledge and use of these practices, whereas negative attitudes may prevent teachers from using them. Encouraging positive attitudes toward EBPs may help enhance the knowledge and use of EBPs (Paynter and Keen, 2015). Thus, further research should study teachers' attitudes toward EBPs and how their attitudes influence their selection of practices and evaluate the effectiveness of training programs in positively changing teachers' attitudes toward EBPs and how this effort assists in enhancing teachers' knowledge and use of EBPs.

This study focused on a closed list of EBPs and thus excluded non-EBPs. The literature has indicated that participants frequently use non-EBPs (Hess et al., 2008; Burns and Ysseldyke, 2009; Carter et al., 2011, 2012). Thus, the teachers in this study may have used several non-EBPs, in addition to using EBPs. Thus, further research should measure and compare teachers' knowledge and use of EBPs and of non-EBPs, to provide a clear picture of the practices used inside the classroom. Sometimes, teachers need to know EPBs and non-EBPs so that they focus on using EBPs and avoid other practices. As a result, pre- and in-service training programs should provide information on EBPs and non-EBPs so that teachers understand the differences in the examples and non-examples of EBPs.

## CONCLUSIONS

This study is among the first to examine teachers' knowledge and use of EBPs in developing countries. The results indicate that teachers have a satisfactory level of knowledge and use of EBPs for students with ASD. Knowledge and use of EBPs were related. Gender and professional development programs were predictors of teachers' use of EBPs for students with ASD. This finding suggests that improving teachers' knowledge of EBPs for students with ASD could increase teachers' use of that practice. Thus, offering high-quality professional development programs could improve teachers' use of EBPs for students with ASD. Teachers should be encouraged and required to attend the professional development programs on EBPs. In addition, school district leaders should develop handbooks and websites (Test et al., 2015) on EBPs to reach teachers, regardless of location. However, this study assessed perceived knowledge and self-reported use; thus, further research could measure the actual knowledge and use of these practices.

## 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 study was conducted after approvals were granted from the College of Education at King Saud University and the General Administration of Education in Riyadh. Written informed consents were obtained from participants and were kept confidentiality. The patients/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.

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# Examining Distinctive Working Memory Profiles in Chinese Children With Predominantly Inattentive Subtype of Attention-Deficit/Hyperactivity Disorder and/or Reading Difficulties

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Although evidence has shown that both RD and ADHD-I children suffer from working memory problems, inconsistencies in impaired modalities have been reported. This study aimed to (1) compare the three WM domains (i.e., verbal WM, visual-spatial WM, and behavioral WM) among pure ADHD-I, pure RD, comorbid ADHD-I + RD, and typical control groups and (2) examine the impact of comorbidity on the three WM domains. A Chinese sample of participants from Hong Kong included 29 children in the ADHD-I group, 78 children in the RD group, 31 children in the comorbid group (ADHD-I + RD), and 64 children in the TD control group. All participants completed the assessments individually. The findings showed that the children with ADHD-I and/or RD exhibited diverse cognitive profiles. In particular, RD was associated with verbal and visual-spatial working memory deficits, while ADHD-I was associated with behavioral working memory deficits. Interestingly, the comorbid condition demonstrated additive deficits of the two disorders but with greater deficits in behavioral working memory. These findings support the cognitive subtype hypothesis and provide a clearer picture of the distinctive working memory profiles of different groups, allowing for the development of intervention programs in the future.

**Keywords: attention-deficit disorder, children, dyslexia, inattentive subtype, reading difficulties, working memory**

## INTRODUCTION

### Attention-Deficit/Hyperactivity Disorder and Reading Difficulties

Attention-deficit/hyperactivity disorder (ADHD) is one of the most common neurodevelopmental disorders in children worldwide, with 8.4% of school-aged children having ADHD [American Psychiatric Association (APA), 2021]. According to the Diagnostic and Statistical Manual of Mental Disorders (DSM-V), ADHD can be divided into three subtypes: the predominantly inattentive subtype (ADHD-I), predominantly hyperactive/impulsive subtype (ADHD-H), and combined subtype [ADHD-C; American Psychiatric Association (APA), 2013]. A recent meta-analysis revealed that ADHD-I is the most common ADHD subtype, followed by ADHD-H and ADHD-C (Ayano et al., 2020). Characterized by a range of behavioral problems, such as difficulty attending to instructions, focusing on tasks, and keeping up with tasks following instructions, the ADHD-I subtype differs from the more commonly recognized ADHD-C subtype, in that symptoms of hyperactivity and impulsivity are minimal or absent (Hurtig et al., 2007). Some evidence suggests that children with ADHD-I may be more academically impaired than those with the ADHD-C subtype (e.g., Weiss et al., 2003; Trampush et al., 2009).

In fact, children who exhibit purely inattentive behavior are likely to underachieve in reading (Warner-Rogers et al., 2000; Willcutt and Pennington, 2000) and have a significantly higher rate of comorbid reading difficulties (RD) than in any other developmental disorder (Turker et al., 2019; Karr et al., 2021). These RD occur despite normal intelligence and a lack of sensory impairment, brain damage, or environmental deprivation (McBride-Chang, 1995; Catts and Kamhi, 2005) and have a global prevalence rate of 7% in children (Dyslexia International, 2021). The comorbidity of ADHD-I and RD in children is 31–45% (DuPaul et al., 2013; Children and Adults with Attention-Deficit/Hyperactivity Disorder (CADD), 2021), an estimate that exceeds the expected chance occurrence (Mueller and Tomblin, 2012). Furthermore, this overlap occurs in both community and clinical samples, suggesting that it is not a selection artifact (Willcutt et al., 2001). More importantly, individuals with comorbid ADHD-I and RD are a group that is understudied. Given the high prevalence rate and developmental challenges this group faces (Bloom et al., 2005), the current study aimed to explore the core neurological deficits of ADHD-I and RD and understand the impact of comorbidity on these shared deficits.

## Working Memory Deficits: Construct and Measurements

Extensive evidence has shown that both RD and ADHD-I children suffer from working memory (WM) problems (Schweitzer et al., 2006; Fostick and Revah, 2018). WM is a multicomponent system providing temporary storage of information for brief periods of time that can be used to support ongoing cognitive activities (Baddeley and Hitch, 1974; Baddeley, 1983, 2012; McCabe et al., 2010). A large body of research has focused on WM deficits in individuals with difficulties in reading (e.g., Gray et al., 2019; Kofler et al., 2019) and attention (Barkley, 1997; Martinussen and Tannock, 2006). For instance, Engle (2002) suggested that WM is highly related to reading, as it helps to maintain or suppress information related to word processing, such as segmentation and blending. At the same time, WM is the capacity for controlled and sustained attention in the face of interference or distraction, which is the ability children with attention-deficit lack (Shipstead et al., 2014). Research has also identified that WM, rather than inhibitory control, is the primary cognitive deficit in ADHD-I vs. ADHD-C (e.g., Diamond, 2005; Huang-Pollock and Karalunas, 2010).

The limited capacity of WM varies widely among individuals. The cognitive and behavioral profiles are the two major directions for understanding individual differences in WM. The cognitive profile is mostly based on the multicomponent model (Baddeley, 2003), which conceptualizes WM as a system with three major components: a central executive component, a phonological loop, and a visuospatial sketchpad (Cocchini et al., 2002; Baddeley, 2012). Both the phonological and visual components belong to the executive component and are referred to as "slave" systems because they hold information for very short periods of time. Considering the entirely different input sensory of the two components, individual differences in WM capacity are assessed by separate techniques that are designed to impose significant concurrent demands on both processing and storage (e.g., Daneman and Carpenter, 1980). In tests of phonological or verbal WM, the participant is required to recall sequences of verbal material, such as digits, words, or non-words (Green et al., 2012). Visuospatial WM tests, on the other hand, involve the presentation and recall of materials, such as sequences of tapped blocks or filled cells in a visual matrix (Alloway et al., 2008b).

Other studies have adopted behavioral measures, such as the Working Memory Rating Scale (WMRS; Alloway et al., 2008a) and the WM subscale of the Behavior Rating Inventory of Executive Function (BRIEF; Alloway et al., 2009; Beck et al., 2010) as behavioral profile measures. Some research (e.g., Shakehnia et al., 2021) has used behavioral measures to evaluate children's WM within their lived environments (i.e., at home or at school) with information gained from parents or teachers. For instance, questions were asked about forgetting lengthy instructions, missing letters or words in sentences, and frequently making careless errors. Interestingly, some studies have shown that performance measured by a behavioral scale did not indicate concordance with the direct cognitive measures of the two slave systems (Sullivan and Riccio, 2007; Biederman et al., 2008), suggesting it might not evaluate the same skills as those measured by direct cognitive tests. Other studies have suggested that behavioral rating measures and conventional direct measures of WM are significantly related (e.g., Alloway et al., 2008b). Undoubtedly, the combined use of the cognitive and behavioral profiles would provide valuable complementary information to improve our understanding of WM in children with these two disorders.

## WM Deficits in ADHD-I and/or RD Using Cognitive vs. Behavioral Measurements

Although evidence has shown that both RD and ADHD-I children suffer from WM problems, inconsistencies in the impaired modalities have been reported. Previous epidemiological studies have suggested that ADHD-I is likely to be associated with poorer verbal (Wu et al., 2006; Ferrin and Vance, 2014) and visual-spatial WM (Brocki et al., 2007; Cockcroft, 2011; Dovis et al., 2015). However, others have failed to replicate the results (e.g., Geurts et al., 2004; Jonsdottir et al., 2005; Kibby and Cohen, 2008). Nevertheless, the studies that used behavioral measures were more consistent in their findings that children with ADHD-I exhibited a range of behavioral WM deficits (Alloway et al., 2010; Cockcroft, 2011; Holmes et al., 2014; Dovis et al., 2015), especially concerning distractibility and the inability to focus their attention in the face of interference (Engelhardt et al., 2010).

Verbal WM deficits, on the other hand, have been associated with children with RD (Gathercole and Pickering, 2000; Baddeley, 2003; Gathercole et al., 2003; Alloway et al., 2009). For instance, poor verbal WM has been shown in logographic language (Ho et al., 2004; Chan, 2018; Chen et al., 2018) and alphabetic languages (Lehtola and Lehto, 2000; Swanson and Jerman, 2007; Pham and Hasson, 2014). Previous research has yielded mixed results for visual-spatial WM in children with RD (Pham and Hasson, 2014). Regarding behavioral WM, studies using the BRIEF scale have shown that children with RD tend to have difficulties associated with reading-related WM, such as short attention spans, struggling with tasks that have more than one step, and recalling only the first or last when given three things to do (Daucourt et al., 2018; Akyurek and Bumin, 2019). In general, studies have shown individuals with RD to exhibit significantly weaker verbal WM than visual-spatial WM (Bayliss et al., 2005) and behavioral WM (Savage et al., 2007), suggesting that verbal WM plays a more significant role in reading.

When examining the impact of comorbidity, many studies have confirmed that cognitive deficits seem to be more severe in the comorbid group (de Jong et al., 2006). Martinussen and Tannock (2006) revealed that children with ADHD-I and RD were impaired in both verbal and visual-spatial domains of WM. A study conducted by Katz et al. (2011) showed that children with both disorders had more difficulties on virtually all cognitive measures of WM than individuals who had pure disorders. To date, no study has compared the cognitive and behavioral profile of WM among the three subgroups or explored the impact of comorbidity ADHD-I+RD on the comprehensive profile of WM.

To understand the impact of comorbidity, three mutually exclusive hypotheses reign. Early studies proposed the “phenocopy hypothesis,” according to which one disorder might produce symptoms of the other. For example, Pennington et al. (1993) concluded that RD and ADHD may be a phenotype of RD, in that RD causes symptoms in patients with RD and ADHD, rather than ADHD. The second hypothesis is the “common etiology hypothesis,” according to which distinct cognitive deficits appear in groups with pure disorders, while the comorbid group manifests the additive set of symptoms. This hypothesis suggests that the ADHD+RD group shares the basic characteristic impairments of executive dysfunction with the ADHD-only group and impairments in reading-related cognitive functions with the RD-only group. Some evidence has supported the common etiology hypothesis and suggested that the comorbid ADHD+RD group shares the common cognitive risk factors and genetic underpinning of the pure groups (e.g., Willcutt et al., 2005; Gooch et al., 2012). Finally, the “cognitive subtype hypothesis” proposes that the interaction between two pure disorders results in a unique form of cognitive impairment in the comorbid group. In other words, neuropsychological deficits in the ADHD+RD group are different from the simple additive combination of deficits associated with children with either RD or ADHD only. The most recent findings support this hypothesis. For example, Poon and Ho (2014) reported that the ADHD+RD group displayed a greater problem of executive control than the RD-only or ADHD-only groups. Moreover, Wang and Chung (2018) reported that Chinese children with comorbid ADHD+RD displayed greater deficits in auditory WM than did the pure groups. In sum, these three controversial hypotheses are still being tested, and the nature of children with comorbid ADHD and RD symptoms remains unclear (de Groot, 2015). A possible explanation for this inconsistency may be the various abilities and skills involved in different studies that produce complicated results. Interestingly, almost all of these studies focused on the ADHD combined subgroup, leaving the most commonly seen ADHD-I subtype underexplored. The present study addressed this research gap by investigating the shared cognitive deficit, WM, in the ADHD-I, RD, and ADHD-I+RD subgroups and exploring the impact of comorbidity.

### Aims of the Study

The purposes of this study were as: (1) to compare the three WM domains (i.e., verbal WM, visual-spatial WM, and behavioral WM) among the pure ADHD-I, pure RD, comorbid ADHD-I+RD, and typical control groups and (2) to examine the impact of comorbidity on the cognitive and behavioral WM domains. Based on previous research, it was hypothesized that children with ADHD-I would be associated with deficits in behavioral WM, while children with RD would be associated with deficits in verbal WM. It was also hypothesized that the comorbid group of ADHD-I and RD would exhibit severe forms of WM deficit shared by the pure groups, which supported the cognitive subtype hypothesis.

## MATERIALS AND METHODS

### Participants

Two hundred and two primary school students ($M_{age} = 9.3$; $SD = 1.1$) were recruited from four primary schools in Hong Kong. This sample size was estimated using G*Power (Faul et al., 2009), with Cohen’s $f$ (Cohen, 1988) medium effect size of 0.25, an alpha level of 0.05, and 80% statistical power. In Hong Kong, there are approximately 7.4 million people and 8.2% of whom are children aged between 6 and 11 years (Census and Statistics Department, 2021). The prevalence rates of ADHD-I and RD are 6.4% (Liu et al., 2018; Hong Kong Association for AD/HD, 2021) and 9.7%, respectively (Child Assessment Service, Department of Health, 2017). A multi-stage sampling procedure was used to obtain the sample. Mass invitations were sent to all public primary schools in Hong Kong and schools to be studied were then randomly selected such that the proportion of students in each selected district represented the number of students in that area. This procedure resulted in the selection of four schools, respectively, with one from Hong Kong Island, another from Kowloon Peninsula, and two from the New Territories. As schools were given the option to withdraw from participation, a further four schools were selected by the same procedure as a backup. Schools that withdrew from participation would be replaced by schools on the back-up list from the same district. Of the schools originally selected, none withdrew from participation. Only children who had been formally diagnosed with ADHD and/or RD prior to the beginning of this study were recruited to participate in this study. The inclusion criteria were as: (1) aged between 6 and 11; (2) overall IQ score above 80; (3) a clinical diagnosis of ADHD and/or RD from a clinical or educational psychologist or a psychiatrist; and (4) native speaker of Cantonese. The exclusion criteria were as: (1) suspected brain damage, neurological, sensory, or other psychiatric disorders. After screening, the final sample included 29 participants ($M_{age} = 9.6$; $SD = 1.1$; age range: 7–11 years) in the ADHD-I group, 78 participants ($M_{age} = 9.1$; $SD = 1.0$; age range: 7–11 years) in the RD group, 31 participants ($M_{age} = 9.7$; $SD = 1.3$; age range: 7–11 years) in the comorbid group, and 64 participants ($M_{age} = 9.0$; $SD = 1.0$; age range: 7–11 years) in the TD group. All of them had normal intelligence (≥80) and no suspected brain damage or neurological, sensory, or psychiatric problems.

## Procedures

Ethics approval was obtained through the first and second authors' institution prior to the commencement of data collection. Before collecting data, the authors contacted the school principals to request their permission to approach the primary school students who are interested taking part in this research. All participants were informed of the research objectives, procedures, and confidentiality of the information obtained from the participants and anonymity. Informed consent forms were then given to the parents and children to obtain their consent to participate. Upon receiving the signed consent forms from the parents, their children completed the cognitive assessments during the screening and assessment phases.

## Screening Phase

Students with ADHD-I and RD diagnoses were identified based on the comprehensive psychological reports conducted by clinical or educational psychologists or psychiatrists. The comprehensive reports include results from the standardized psychological assessments on students' abilities in reading and writing {e.g., The Hong Kong Test of Specific Learning Difficulties in Reading and Writing for Primary Students—Third Edition [HKT-P(III)]} (Ho et al., 2016) as well as their specific ADHD symptoms (e.g., performance on the Conners Continuous Performance Test; Conners et al., 2018). The authors obtained the relevant information from the schoolteachers after parents gave consent. All students had a formal clinical diagnosis of ADHD-I and/or RD. Those who were diagnosed with ADHD-I were on medication. The paper-and-pencil version of Raven's Standard Progressive Matrices (Raven et al., 2000) was then administered to the participants to rule out any intellectual disability. The entire screening phase took approximately 30 min.

## Assessment Phase

During the assessment phase, the third edition of the backward digit span subtest from the Wechsler Intelligence Scale for Children (WISC-III; Wechsler, 1991) and the visual-spatial WM test from the Cambridge Neuropsychological Test Automated Battery (Cambridge Cognition Limited, 2021a) was administered to the students individually. Their parents were also asked to fill out the WM subscale of the BRIEF (Gioia et al., 2000). The individual assessments lasted approximately 30 min. A detailed description of all cognitive tasks is provided below.

## Measurements

Participants' demographic background information (e.g., age, sex, and education level) was collected using self-report. A comprehensive assessment battery of WM tasks was also administered to the participants, and data on reading performance and behavioral outcomes were collected from multiple informants (i.e., parents) using questionnaires.

### Intellectual Ability

Raven's Standard Progressive Matrices (Raven et al., 2000) were used to assess general intellectual ability. This test contains 60 items in total, and each item consists of a visual pattern with a missing piece; participants were asked to identify the correct piece to fill in the missing part and complete the pattern; and those who scored below 80 were excluded from the present study. The Raven's test has good internal consistency, with a Cronbach alpha coefficient reported of 0.88 (NCS Pearson, Inc, 2007).

### Behavioral WM

The BRIEF is a standardized measure that allows the observers (i.e., parents) to rate the behavioral measure of WM in children with ADHD. It is a well-researched instrument that provides researchers with a comprehensive assessment tool that results in reliable and valid data (Hendrickson and McCrimmon, 2019). The WM subscale of the BRIEF in Chinese (Gioia et al., 2000) comprises a parent questionnaire designed to assess executive functioning in the home environment. The WM subscale consists of 11 items. Parents were asked to rate their child's behavior on a three-point Likert scale ranging from 1 (*never*) to 3 (*often*). The internal consistency was 0.80–0.98, and the test-retest reliability was 0.82, indicating good reliability of the BRIEF (Gioia et al., 2000).

### Verbal WM

The backward digit span subtest from the WISC-III (Wechsler, 1991) was employed to measure verbal WM capacity. This is one of the most common tools used by researchers (Cheung et al., 2014; Siquara et al., 2018) for the evaluation of memory capacity in children aged between 6 and 16 years, and age-specific norms are provided. The participants were asked to repeat the orally presented digits in reverse order from two to nine. They must maintain auditory information and select relevant information from irrelevant information to recall orally presented digits in reverse order. Age-standardized scaled scoring was used as the outcome measure. The subset of backward digit span has obtained good reliability, with alpha coefficient of $\alpha = 0.80$ (Chen and Hung, 2004).

### Visual-Spatial WM

The spatial WM test was selected from the Cambridge Neurophysiological Test Automated Battery (CANTAB) to measure visual-spatial WM. It has established a large normative data set and has been widely used in research studies, with over 2,400 peer-reviewed papers supporting its use (Cambridge Cognition Limited, 2021b). The test is a computerized standard measure that begins with several boxes on the screen. The participants were asked to search for a yellow token hidden in one of the boxes. In each search, only one token can be found. When the token is collected, participants must search for another until all have been found (the number of tokens is equal to the number of boxes). The token never appears in boxes where one has previously been found. The number of boxes increases from a minimum of four to a maximum of eight when the difficulty level increases. The variable "between error" counts the number of times participants mistakenly search for a box where a token has been found before. A higher number of between errors represents a weaker ability in visual-spatial WM. This CANTAB test falls within an accepted level of test-retest reliability of 0.75–0.80 (Lowe and Rabbit, 1998).

## Data Analysis

Several statistical methods were employed using the Statistical Package for Social Sciences (Version 26.0; IBM Corp, 2019). The demographic characteristics of the participants were investigated using chi-square tests for independence (for nominal variables) and a one-way ANOVA (for continuous variables), followed by post-hoc tests for group comparisons. To achieve the overarching aim of the study, a 2 (ADHD-I vs. non-ADHD-I) × 2 (RD vs. non-RD) multivariate analysis of covariance (MANCOVA) was used, with the three outcome measures serving as dependent variables, and age and IQ serving as controlling variables. A MANCOVA was used to maximize the power to detect significant effects, Pillai's trace was used to determine statistical significance when comparing three levels, and sample sizes were unequal across cells. When justified by significant interaction effects in the MANCOVA, simple effect analyses were followed by group comparisons using Tukey's test to control the probability of committing a Type 1 error.

# RESULTS

With reference to the recommendations by Tabachnick and Fidell (2019), the data were scanned for univariate and multivariate outliers to ensure the accuracy of the data file. No outliers were detected. Standard skewness and standard kurtosis revealed that the data were normally distributed (standard skewness/standard kurtosis $\leq \pm 1.96$).

## Group Differences in Demographic Variables

A one-way ANOVA was conducted to compare the demographic variables, including age, intellectual ability (IQ), and education level, in the four groups. There were significant differences in age [$F(3,198) = 3.87$, $p < 0.05$] and IQ [$F(3,198) = 12.99$, $p < 0.001$]. In terms of age, post-hoc comparisons using the Tukey HSD test indicated that the mean score for the TD group was significantly different from that of the comorbid group ($p < 0.05$). As for IQ, post-hoc comparisons using the Tukey HSD test indicated that the mean score for the TD group ($M = 107.16$; $SD = 15.91$) was significant different from the RD ($p < 0.001$; $M = 93.46$; $SD = 13.72$) and comorbid ($p < 0.001$; $M = 93.06$; $SD = 13.01$) groups. The difference between the ADHD-I ($M = 102.21$; $SD = 13.83$) and RD ($M = 93.46$; $SD = 13.72$) groups was also significant ($p < 0.05$). No significant difference was found in education level [$F(3, 198) = 0.66$, $p = 0.58$] (see **Table 1**).

A chi-square test was used to examine sex differences in each group. Our current study aims to examine the biological and physiological characteristics of our participants as males and females. There was a significant difference in sex [$\chi^2$ (3, 202) = 8.67, $p < 0.05$]. In the ADHD-I group, there were 69% males and 31% females. In the RD group, there were 53% males and 47% females. In the comorbid group, there were 81% males and 19% females. In the TD group, there were 56% males and 44% females (see **Table 2**).

## MANCOVA Results in Three Domains of WM

The scores on the three types of WM were entered into a MANCOVA. After controlling for age and IQ, the multivariate main effects of ADHD-I [$F(3, 170) = 18.86$, Pillai's Trace = 0.25, $p < 0.001$, $\eta_p^2 = 0.25$], RD [$F(3, 170) = 3.26$, Pillai's Trace = 0.05, $p < 0.05$, $\eta_p^2 = 0.05$], and the interaction of ADHD-I × RD [$F(3, 170) = 9.26$, Pillai's Trace = 0.14, $p < 0.001$, $\eta_p^2 = 0.14$] proved to be significant. In the univariate analysis, there were significant main effects of ADHD-I on behavioral WM [$F(1, 172) = 53.98$, $p < 0.001$] and RD on verbal WM [$F(1, 172) = 8.45$, $p < 0.05$]. The main effect of RD on visual-spatial WM was marginally significant [$F(1, 172) = 3.32$, $p = 0.07$]. Furthermore, there were significant interaction effects between ADHD-I and RD in all three domains of WM: behavioral WM [$F(1, 172) = 13.04$, $p < 0.001$], verbal WM [$F(1, 172) = 5.97$, $p < 0.05$], and visual-spatial WM [$F(1, 172) = 5.27$, $p < 0.05$; see **Table 3**].

Given the significant interaction effects, simple effect analyses were conducted. The results revealed that the performance of the three disorder groups (ADHD-I: $p < 0.001$; RD: $p < 0.05$; comorbid: $p < 0.001$) was significantly worse than that of the TD group in behavioral WM. Significant differences were also found between the RD and comorbid groups ($p < 0.001$), between the ADHD-I and RD groups ($p < 0.001$), and between the ADHD-I and comorbid groups ($p < 0.05$) in behavioral WM. The bar chart shows that individuals with ADHD-I status, having RD, had an impact on behavioral WM, while individuals without ADHD-I, having RD, showed no difference in behavioral WM (see **Figure 1**).

**TABLE 1** | Demographic characteristics in ADHD-I, RD, ADHD-I+RD, and TD groups.

| Variable | ADHD-I (n=29) | | RD (n=78) | | 3. ADHD-I+RD (n=31) | | TD (n=64) | | *Post-hoc* |
|---|---|---|---|---|---|---|---|---|---|
| | *M* | *SD* | *M* | *SD* | *M* | *SD* | *M* | *SD* | |
| Age | 9.57 | 1.15 | 9.15 | 1.00 | 9.68 | 1.34 | 9.01 | 0.97 | 4<3 |
| IQ | 102.21 | 13.83 | 93.46 | 13.72 | 93.06 | 13.01 | 107.16 | 15.91 | 4>2, 3<br>1>2 |
| Education level | 3.34 | 0.81 | 3.12 | 0.81 | 3.17 | 1.00 | 3.16 | 0.89 | – |

**TABLE 2** | Results of chi-square analysis to examine sex differences across the groups.

| | Total | | ADHD-I | | RD | | ADHD-I+RD | | TD | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | *N*=202 | | *n*=29 | | *n*=78 | | *n*=31 | | *n*=64 | | |
| | *n* | % | *n* | % | *n* | % | *n* | % | *n* | % | $\chi^2$ |
| Sex | | | | | | | | | | | 8.67* |
| Male | 122 | 60.4 | 20 | 69.0 | 41 | 52.6 | 25 | 80.6 | 36 | 56.3 | |
| Female | 80 | 39.6 | 9 | 31.0 | 37 | 47.4 | 6 | 19.4 | 28 | 43.8 | |

*$p<0.05$.

In terms of verbal WM, the TD group significantly outperformed the ADHD-I ($p<0.01$), RD ($p<0.01$), and ADHD-I+RD ($p<0.01$) groups. No significant differences were found between the other three disorder groups (ADHD-I vs. RD: $p=0.70$; RD vs. comorbid: $p=0.83$; ADHD-I vs. comorbid: $p=0.83$). The bar chart illustrates that individuals without ADHD-I status had an impact on their verbal WM performance. In contrast, for individuals with ADHD-I, RD made no difference (see **Figure 2**).

As for visual-spatial WM, the performance of the TD group was significantly better than that of the RD group ($p<0.01$). The differences between the TD and ADHD-I groups ($p=0.076$) and the TD and comorbid groups ($p=0.086$) were marginally significant. No significant differences were found between the other three disorder groups (ADHD-I vs. RD: $p=0.13$; RD vs. comorbid: $p=0.39$; ADHD-I vs. comorbid: $p=0.79$). The bar chart reveals that individuals without ADHD-I status, having RD, had an impact on their visual-spatial WM performance. Conversely, for individuals with ADHD-I, RD made no difference (see **Figure 3**).

# DISCUSSION

Children with ADHD-I and RD typically show compromised WM abilities, which impacts their learning. Given the emergence of a wider range of validated measures for each of the main components of WM, there is now a need to provide a better understanding of the WM profiles associated with RD and ADHD-I and their comorbidity. This should employ both cognitive and behavioral measures. The current study compared the cognitive and behavioral measures of WM among the four groups and examined the impact of comorbidity on WM. Consistent with our hypotheses, we found that children with ADHD-I were associated with deficits in behavioral WM, while children with RD were associated with deficits in verbal WM and marginally associated with deficits in visual-spatial WM. As for the comorbid group, our findings showed an association with all three WM domains, especially severe impairment in behavioral WM, which supports the cognitive subtype hypothesis. Overall, the results indicate that ADHD-I and RD manifest distinct patterns of WM, which is in line with Kofler et al.'s (2019) conclusion that children with ADHD-I and RD could be attributed to a large proportion of the deficits in WM.

## Research Findings in the RD Group

Consistent with prior literature, children with RD were associated with a deficit in verbal WM. These findings corroborate Martinussen and Tannock's (2006) observation that children with reading disorders exhibited impairments in the verbal domain of WM regardless of the presence of comorbidity with ADHD-I. Further, the current study used a backward digit span subtest, which requires participants to repeat the orally presented digits; this supported previous research showing that a WM deficit in RD is specific to the phonological loop (Ho et al., 2004; Kibby and Cohen, 2008; Chen et al., 2018). Phonological WM deficits, which are significantly associated with RD, have been reported in numerous studies (Szenkovits and Ramus, 2005; Hulme and Snowling, 2013; Lu et al., 2016). The present study showed that there was a marginally significant main effect of RD on visual-spatial WM. In fact, some studies found that children with RD exhibited poorer visual-spatial WM compared to other disorder groups, while other studies found that the visual-spatial WM performance of children with RD was relatively intact compared to children in the TD group (Pham

**TABLE 3 |** Means, standard deviations, and results of 2 × 2 MANCOVA for three types of working memory, with age and IQ as covariates.

| Variable | 1. ADHD-I ($n = 29$) | | 2. RD ($n = 78$) | | 3. ADHD-I + RD ($n = 31$) | | 4. TD ($n = 64$) | | Main effect ADHD-I | | Main effect RD | | Interaction ADHD-I × RD | | Simple effects |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | *M* | *SD* | *M* | *SD* | *M* | *SD* | *M* | *SD* | *F* | $\eta_p^2$ | *F* | $\eta_p^2$ | *F* | $\eta_p^2$ | |
| Behavioral WM | 22.14 | 2.43 | 19.83 | 3.58 | 25.18 | 3.67 | 18.29 | 4.34 | $53.98^{***}$ | 0.24 | 1.76 | 0.01 | $13.04^{***}$ | 0.07 | 4 < 2 < 1 < 3 |
| Verbal WM | 8.73 | 2.53 | 8.31 | 1.87 | 8.49 | 1.49 | 10.04 | 3.17 | 0.39 | 0.00 | $8.45^{*}$ | 0.05 | $5.97^{*}$ | 0.03 | 4 < 1, 2, 3 |
| Visual-spatial WM[1] | 19.98 | 7.14 | 22.22 | 5.95 | 20.63 | 8.21 | 17.31 | 6.01 | 2.46 | 0.01 | $3.32^{\dagger}$ | 0.02 | $5.27^{*}$ | 0.02 | $4 < 1^{\dagger}, 2, 3^{\dagger}$ |

$^{*}p < 0.05$; $^{***}p < 0.001$.
$^{\dagger}$= *marginally significant.*
[1]= *higher number of between errors, indicating a weaker ability in visual-spatial WM.*

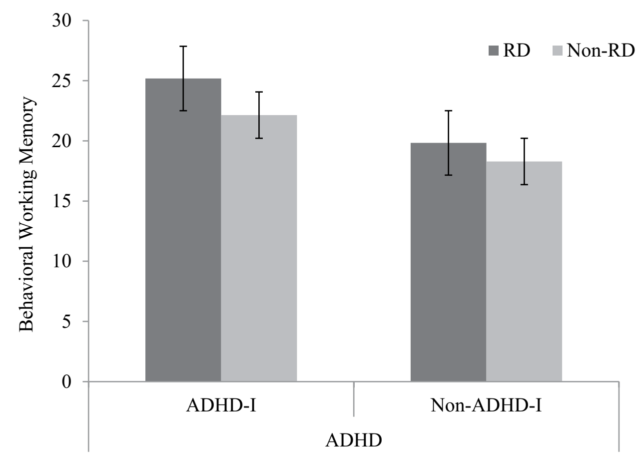


**FIGURE 1 |** Interaction effect of ADHD-I and RD in behavioral working memory.

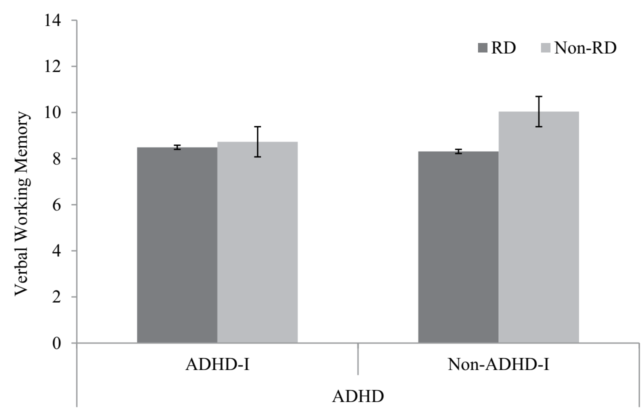


**FIGURE 2 |** Interaction effect of ADHD-I and RD in verbal working memory.

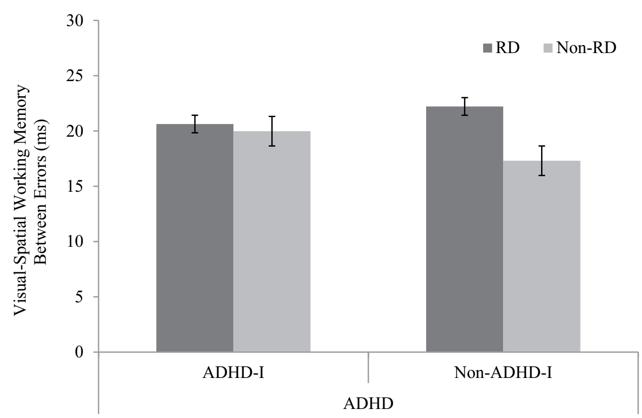


**FIGURE 3 |** Interaction effect of ADHD-I and RD in visual-spatial working memory.

and Hasson, 2014). One possible explanation for these inconsistent findings relates to the complex measures of visual-spatial WM. Our study used a computerized measure that assessed the participants' ability to temporarily store and process information to successfully search for a hidden object; later studies may use more dynamic and comprehensive aspects of visual-spatial tasks, such as tracking visual sequences and transforming visual-spatial images, to examine the link between RD and visual-spatial WM (e.g., Logie, 1995; Duff and Logie, 1999; Alloway et al., 2006). Our findings also showed that RD was not associated with behavioral WM. One of the reasons for this non-significant finding is that the BRIEF rating scale was employed to measure general WM behavior within the home environment, instead of targeting reading-related behavioral WM. Researchers may wish to include other behavioral rating scales that have a stronger focus on reading-related WM measures in future research.

## Research Findings in the ADHD-I Group

Our findings in the ADHD-I group exhibited a main effect in behavioral WM but not in any of the cognitive WM assessments (i.e., verbal and visual-spatial). The ADHD-I group still exhibited comparatively poor cognitive and behavioral WM compared to the control group in our study. Such findings align with earlier studies that correlated ADHD-I with behavioral WM deficits (Wu et al., 2006; Brocki et al., 2007; Barkley and Murphy, 2010; Fuermaier et al., 2013a,b, 2015). Gioia et al. (2002) also revealed that children with ADHD manifested higher scores on the BRIEF scale compared to children with RD. As such, they argued that poor WM is a result of poor attentional control and inhibition. Poor behavioral inhibition is suggested to directly limit an individual's WM, in addition to other important executive functioning abilities, such as self-regulation of affect-motivation arousal and internalization of speech (Barkley, 1997; Gray and Climie, 2016). Limited attentional control allows perceptual interference to directly impact the active maintenance of WM concerning a relevant piece of information (Lavie, 2005).

In the current study, ADHD-I was not associated with any significant weaknesses in the two cognitive WM measures. These findings are consistent with prior research that found slightly reduced or intact visual-spatial WM and verbal WM in the ADHD sample (Martinussen et al., 2005; Rhodes et al., 2012). This is perhaps because the phonological loop is intact in ADHD-I when tasks are more forgiving, such as when lists/stories are longer, allowing for brief fluctuations in attention. Another possible explanation is that stimulant medication may ameliorate visual-spatial and verbal WM in children with ADHD (Bedard et al., 2004; Shiels et al., 2008). Although information relating to medication usage was not provided by the participants in this study, previous research found that individuals with ADHD have a high prevalence of medication use (Russell et al., 2019). Future research should examine the role of stimulant medication in WM performance among Chinese children with ADHD-I.

## Research Findings in the Comorbid Group

With respect to the comorbid group, our study yielded interesting results. On the one hand, children with comorbidity of ADHD-I and RD had similar scores in verbal and visual-spatial WM compared to the pure groups. On the other hand, the score for behavioral WM was significantly higher in the comorbid group than in the other pure groups. It may be possible to conclude that children with pure RD or ADHD-I manifested distinct cognitive deficits, while both forms of deficit occurred together in the comorbid condition and produced an augmented clinical manifestation of behavioral WM deficits. These findings are consistent with a previous study conducted by Willcutt et al. (2005), who found that the comorbid group had worse performance in WM across the behavioral scales. One possible explanation could be the shared neural correlates between ADHD-I and RD. Langer et al. (2019) concluded that a combination of shared and distinctive brain alterations supported the multiple deficit model for ADHD-I and RD that the comorbid group showed greater impairments on all the same measures.

## Limitations and Conclusion

Some limitations of the present study should be noted. First, the dosage of ADHD medication taken by children with ADHD-I was not reported by the parents. Previous research reported that low doses of ADHD medication improve WM, whereas high doses impair WM in a group of children (Vance, 2008). Therefore, it would be interesting to compare WM performance between participants on high and low doses of ADHD medication in future research into Chinese children with ADHD-I. Second, given that there are other subtypes of ADHD (i.e., hyperactive/impulsive and combined types) and that the severity of symptoms varies across these subtypes, future research should explore whether ADHD symptoms would manifest differently in each of the WM domains. Third, given the relatively small sample size and unequal sizes across groups, the results should be confirmed with a larger Chinese sample of children with ADHD-I and/or RD. Fourth, this is the first study to compare different WM profiles using cognitive assessment batteries and the behavioral rating scale. In the present study, the comorbid group of children with ADHD-I+RD exhibited considerable deficits in behavioral WM, which was consistent with the view that ADHD is heterogeneous in nature (Luo et al., 2019). Behavioral assessment does not require any training prior to the use of psychometric scales and is valuable in identifying children at risk of poor WM (Alloway et al., 2010). The BRIEF rating inventory (Gioia et al., 2000) illustrates both home and school environments in which WM failures occur. It provides an initial step in identifying possible WM deficits prior to performing any additional cognitive tests (Alloway et al., 2010). Although comprehensive cognitive and behavioral assessments could assist in identifying specific structural or functional areas of WM on which to focus intervention, future research should also include WMRS. Understanding the scope of each type of assessment is crucial for the timing of the administration of cognitive functioning tests (Hartman and Blough, 2013). Finally, the current study reported a significant difference in the sex ratio among the four subgroups. In particular, more males were identified in the ADHD-I (69%) and comorbid (81%) groups. Sex differences in the prevalence of ADHD-I and comorbid diagnoses are well documented in the literature (Ramtekkar et al., 2010; Willcutt, 2012; Skogli et al., 2013), yet the underlying reasons for the observed differences remain to be investigated (Elkins et al., 2011; Kan et al., 2013). Although in-depth exploration is beyond the scope of this paper, there is evidence supporting sex disparity in WM, especially when WM is deconstructed into spatial and verbal components. Further research is therefore warranted to understand whether there are sex-based differences in the WM domains in children with ADHD-I and ADHD-I + RD groups (Pham and Hasson, 2014).

Despite these limitations, our findings have potential implications. The present study was a response to earlier calls for targeted interventions for ADHD-I, RD, and comorbid groups of children. These include computerized training targeting WM, which has been associated with a reduction in ADHD symptoms and an improvement in the visual domains (e.g., Flak et al., 2019). For example, Klingberg et al. (2005) tested the effectiveness of a five-week WM training program on students with ADHD and found that it significantly improved their WM capacity and behaviors. In addition, Luo et al. (2013) conducted computerized WM training focused on visual-spatial WM, verbal WM, and central executive tasks for children with RD. They found that intensive and adaptive computerized WM training contributed to a gradual increase in WM capacity. In particular, they observed a significant improvement in visual rhyming and reading fluency tasks. Another alternative would be to supplement verbal instruction with visual aids and demonstrations for children with RD.

In conclusion, this study indicated that children with ADHD-I and/or RD exhibited diverse cognitive profiles, particularly in the Chinese population in Hong Kong. Children with comorbid symptoms demonstrated poorer performance in behavioral WM than those in the pure groups. Furthermore, children in the RD group demonstrated weaker ability in verbal WM and visual-spatial WM than did the pure groups. These findings provide a clear picture of the distinctive WM profiles across different groups, allowing for the development of intervention programs in the future.

## DATA AVAILABILITY STATEMENT

The original contributions presented in the study are included in the article/supplementary material, and further inquiries can be directed to the corresponding author.

## ETHICS STATEMENT

The studies involving human participants were reviewed and approved by the Human Research Ethics Committee, The Education University of Hong Kong. Written informed consent to participate in this study was provided by the participants' parents.

## AUTHOR CONTRIBUTIONS

KP was responsible for the conception of the research questions, study design, data interpretation, and writing. MH was responsible for data analysis and writing. L-CW was responsible for providing input on this paper. All authors have agreed the final version of the manuscript.

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# An Investigation of Mathematics Anxiety and Academic Coping Strategies Among High School Students in Vietnam: A Cross-Sectional Study

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Increasing numbers of students around the world are suffering from mathematics anxiety. The main objective of this study is to investigate the relationship between mathematics anxiety and gender, grade, career choices, and academic achievement in Grade 10, 11, and 12 students. This study used the Revised Version of the Mathematics Anxiety Rating Scale to survey 1,548 high school students (570 males and 978 females) from high schools in Vietnam. A multivariate analysis of variance (MANOVA) test, Pearson correlation and multiple linear regression were used to analyze data. The results show that there are significant differences in the influence of grade, academic achievement, and students' career choices on mathematics anxiety. Academic coping strategies, gender, grade, and career choices are significant predictors of mathematics anxiety. Grade 12 students have higher levels of mathematics anxiety than others. Students with high average mathematics scores (9.0–10.0) have higher levels of mathematics anxiety than students with lower scores. Besides, students choosing finance and economics or industrial engineering to pursue into higher education also experienced higher levels of mathematics anxiety than others. This study contributes to the general discussion about the nature of mathematics anxiety and the relationship between mathematics anxiety and academic achievement.

**Keywords: mathematics anxiety, high school student, academic achievement, academic coping strategies, average mathematics score, gender, career choice, grade**

## 1 INTRODUCTION

Industrial Revolution 4.0 has had a considerable influence on many aspects of society, including not only economic development (optimising production processes through digital and intelligent technologies) but also the transformation of education. The economy now demands new management systems and improvements in the skills of the whole population, especially students. Thus, education in Vietnam has been transformed under the Education 4.0 initiative to deliver high quality, appropriately skilled human resources to society. This transformation has introduced curricula with complex academic content that requires cognitive flexibility, critical thinking, and creativity. These requirements create numerous challenges in the learning process, including the availability of appropriate material resources and the effects of environmental conditions and, especially, psychological conditions. The resultant academic pressure, stress and anxiety cause loss of energy among students, as well as reduced motivation and difficulty concentrating in class.

Wiedemann (2015) suggested that anxiety is characterised by nervousness and fear, with physical manifestations including tremors, increased pulse rate, and muscle pain. Anxiety is a basic human emotion that generates physiological reactions to stressors when a "fight or flight" defence response is activated in order to protect the individual from a threatening object or phenomenon (Sue et al., 2015).

In the Vietnam context, Mathematics is an important and compulsory subject for all students in the educational system from primary to high school. At each different grade level, the knowledge of mathematics is continuously improved. Therefore, the pressure easily comes when students have to acquire a large amount of mathematics knowledge, take and prepare for mathematics exams. Specifically, mathematics is a compulsory subject in entrance and graduation exams. These have increased more and more pressure on high school students when they have to tackle mathematics problems in the classroom, have a good performance in mathematics and prepare for the school graduation exams at the same time. For these reasons, the authors were interested in mathematics anxiety levels of high school students in Vietnam. Mathematics anxiety includes tension and emotions that affect the ability to manipulate numbers and tackle issues associated with mathematics in day-to-day situations (Richardson and Suinn, 1972). McAnallen (2010) suggested that mathematics anxiety is a response associated with avoiding mathematics that leads to a failure to gain critical skills and, ultimately, to make appropriate decisions on career orientation.

Specific research questions posed of this study:

1) What do factors affect the levels of mathematics anxiety among high school students?
2) How do academic coping strategies influence high school students' anxiety?

Male and females have differences in the substantial aspects of life including the attraction to the mathematics domain (Keshavarzi and Ahmadi, 2013); spatial processing ability (Maloney and Beilock, 2012); stress reactivity (Altemus et al., 2014) and social stereotypes about women and mathematical abilities (Beilock et al., 2007). Therefore, gender difference became the first variable that the authors were interested in examining. Besides, each student has the ability to learn maths and mathematics knowledge absorption differently from others, which leads to differential academic pressure on high school students. Accordingly, their academic achievements and performances in maths are not the same. This proves that mathematics average score should be the following variable affecting the levels of mathematics anxiety which the authors need to be researched on.

Studies investigating the level of mathematics anxiety in high school students have revealed contradictory findings about gender differences in the relationship between mathematics anxiety and academic performance. Keshavarzi and Ahmadi (2013) studied 834 high school students in Iran and reported a non-significant difference between the genders in mathematics anxiety. Another scientific study on mathematics test anxiety and numerical anxiety surveying the mathematics achievement of 140 pre-university students reported that males and females suffer the same level of mathematics anxiety. Akbayir (2019) also found that there is no gender difference in mathematics anxiety. Nevertheless, recent studies have shown a gender difference in the levels of mathematics anxiety. The study by Lew and Hwang (2019) on 459 high school students (124 male and 335 female) from four high schools in Seoul, Korea, showed that mathematics anxiety is significantly higher among female students than male students. The results of Lew and Hwang's study are in agreement with several prior studies. In research on mathematics anxiety in China with students from Grade 7 to Grade 12, Luo et al. (2009) found that females suffer from a greater degree of mathematics anxiety than males. A similar conclusion was reached by Karimi and Venkatesan (2009) who conducted research on 284 Grade 10 students in Karnataka state, India, and found differences in mathematics anxiety according to gender. This finding is also supported by a study by Maloney and Beilock (2012), which showed there are gender differences in mathematics-associated competencies and that females have higher levels of mathematics anxiety. In addition, Taylor and Fraser (2013) suggested that girls experience higher anxiety levels about mathematics evaluation than boys in mathematics learning.

Several scientific studies have focused on the negative effects of mathematics anxiety. Puteh and Khalin (2016) found a negative relationship between mathematics anxiety and mathematics achievement based on the results of mid-term examinations. Zakaria et al. (2012) showed that there is a correlation between academic achievement and mathematics anxiety; the higher the anxiety score, the poorer the academic achievement. According to the authors, the reason for this finding could be a relationship between students' comprehension of mathematics, and their confidence. A study by Karimi and Venkatesan (2009) on 284 high school students showed that there is a statistically negative relationship between mathematics anxiety and mathematics scores. This finding supports the prior study of Woodard (2002), which revealed that students with a high level of mathematics anxiety attain lower mathematics scores than those with a low level of mathematics anxiety. This result implies that students with high levels of mathematics anxiety perform less well in mathematics. Similarly, Lew and Hwang (2019) found that mathematics anxiety is negatively associated with academic achievement. Likewise, in a study involving 514 high school students, Milovanović (2020) showed that there is a significant negative correlation between students' average grades in mathematics and mathematics anxiety.

In the Vietnam context, each grade level has different mathematical problems. In grade 10 and grade 11, students have many pressures and difficulties in adapting new mathematics concepts, principles and formulas, which leads to worries and concerns among these students. In the last year of high school, grade 12, students have to make a decision of future career orientation and attempt to study for examination entrance. Moreover, maths is the crucial requirement of each ology in university, consequently, students in this period of time have more considerable anxiety than others. Therefore, the authors examine the relationship between grade levels variable and mathematics anxiety levels. The effects of grade level (school year) on students' mathematics anxiety have been examined by numerous educators and researchers. The study by Luo et al. (2009) of Grades 7 to 12 in China did not find evidence of statistically significant differences in mathematics anxiety between students but did find that the mean level of anxiety differed according to grade. Specifically, the level of mathematics anxiety was found to rise steadily from Grade 7 to 9, with a greater proportion of students in Grade 9 than in other years experiencing the highest anxiety level. The results showed a considerable decline in the levels of anxiety from Grade 9 to 10, but anxiety then peaked again in Grade 11 before declining again in Grade 12. Jackson and Leffingwell (1999) found a different pattern, with mathematics anxiety beginning in elementary school and growing through high school and the first year of college. Lew and Hwang (2019) found that levels of mathematics anxiety in Grade 11 students are the highest and in Grade 12 students the lowest. Likewise, with data collected from 1,352 Grade 8 to 11 students in Bahrain, Al Mutawah (2015) found that Grade 11 students suffer greater mathematics anxiety than other students.

Further studies mention other factors affecting the levels of mathematics anxiety among students. Mathematics anxiety causes students to tend to quit mathematics courses (specifically advanced mathematics courses) and adopt pessimistic attitudes towards activities that include mathematics, avoiding degree subjects and occupations that require quantitative skills (Hembree, 1990; Ma, 1999; Ho et al., 2000). Yüksel-Şahin (2008) surveyed Grade 4 and 5 students and concluded that individuals who have positive feelings about their mathematics classes experience lower levels of mathematics anxiety. Similarly, students who are positive about their mathematics teacher experience significantly lower levels of mathematics anxiety. In addition, Yüksel-Şahin (2008) suggested that students with higher levels of accomplishment in learning mathematics have lower levels of mathematics anxiety. Bursal and Paznokas (2006) found that negative experiences in school can increase the level of mathematics anxiety; criticism and intimidation by teachers might create an intimidating classroom atmosphere in which students are uncertain about asking or responding to questions. Teachers who punish students by giving mathematics assignments create negative attitudes towards mathematics (Oberlin, 1982). Mathematics anxiety could be brought about by low scores or failure in mathematics (Ma and Xu, 2004), leading to extremely negative feelings about the subject. Given the problems related to academic achievement and performance, it is essential to conduct further scientific research on students' anxiety in general, and mathematics anxiety in particular.

Factors affecting students' career choices have been extensively investigated by researchers. Authors suggest that there are several highly influential factors, such as self-efficacy appraisals of competencies in attaining performance, outcome expectations and desired objectives (Lent et al., 1994), gender role stereotypes (Singer and Stake, 1986), parental attitude (Mau et al., 1995), and social encouragement from friends (Lent et al., 2002).

However, few studies have investigated the influence of mathematics anxiety on students' career choices. Ashcraft (2002), and Ashcraft and Kirk (2001), suggested that mathematics anxiety directly and indirectly affects engagement in courses related to mathematics, attitudes towards mathematics, and career orientation. Anxiety affects the selection of degree courses that depend on the manipulation of numbers or include topics associated with mathematics (Hackett, 1985). Anxiety can also lead to refusal to participate in mathematics classes and avoidance of careers in finance and other fields related to mathematics (Ma, 1999; Kyttälä and Björn, 2010). These findings demonstrate consistency with studies conducted by Betz (1978), and Zettle and Houghton (1998), who suggested that students suffering from mathematics anxiety are more likely to avoid classes and careers associated with mathematics. Specifically, mathematics anxiety could reduce confidence in students' ability to complete mathematics-related tasks and limit students'career choices (Espino et al., 2017).

In the academic environment, although every student has the same learning environment, the same syllabus and so on, all of the students have different academic achievement and performance. This indicates that each high school student has their own coping strategies. Owing to this reason, the authors were interested in coping strategies and conducted this study to examine the effects of coping strategies on mathematics anxiety. The concept of coping strategies has been described in many previous studies. These strategies relate to cognitive and behavioural approaches to alleviating negative emotions that derive from difficult situations and stressful events, which could include academic failure, failure to complete tasks, and performing badly in tests (Lazarus, 2013; Ader and Erktin, 2010). Previous studies on academic coping relate to how students deal with academic challenges, obstacles, and difficulties; the findings of Krypel and Henderson-King (2010) show that these efforts can have either positive or negative aspects. Recent studies (Friedel et al., 2007) have indicated that coping strategies are divided into two main categories: adaptive coping strategies with positive outcomes, and maladaptive coping strategies with negative outcomes. Students with adaptive coping strategies tend to identify and analyse their own mistakes and reframe situations in a positive light. On the other hand, students with maladaptive coping strategies tend to blame their problems on everyone else and ignore their mistakes. Several instruments are available to assess students' coping strategies in academic contexts. The items in the positive coping group are used to measure adaptive strategies when students have poor experiences with mathematics, find their mistakes and improve their performance. Conversely, items in the projective, denial, and non-coping groups measure maladaptive strategies in terms of feelings, thoughts and behaviours when students face difficult problems in school. With projective coping, students tend to blame others for their problems, especially teachers. With denial coping, students ignore their own failures and crucial negative events in mathematics. With non-coping, students tend to blame and criticise themselves for their failures and worry about what others think of their mistakes (Friedel et al., 2007). Skaalvik (2018) found that use of coping strategies among students when dealing with mathematics is significantly predictive of mathematics anxiety. Students who have problem-focused coping strategies, finding out their mistakes and resolving to do better next time, are negatively associated with mathematics anxiety.

In Vietnam, anxiety among students is seen as an important topic. Thanh Tra (2019) conducted scientific research on levels of anxiety with 500 university and college students in Ho Chi Minh City and reported a high level of anxiety, identifying factors that have a negative impact on the mental health of students. In addition, Van (2018) showed that a large number of high school students in Ho Chi Minh City suffer from academic anxiety caused by false beliefs and cognitive distortion of themselves, problems in their relationships with teachers, and academic pressure from their parents.

Increasing numbers of students around the world are suffering from mathematics anxiety, which has negative effects on learning outcomes and academic achievement. It also creates obstacles in the learning process. This current research is conducted to examine mathematics anxiety among Vietnamese high school students and test the correlation between students' mathematics anxiety and academic coping strategies.

The research starts by reviewing the literature on mathematics anxiety in high school students. A research methodology is presented in the second section. In the following sections, the research results and discussion are introduced. Research on mathematics anxiety could make a major contribution to preventing anxiety among high school students, protecting and enhancing students' mental health during the learning process.

The first hypothesis is that students in Grade 12 have higher levels of mathematics anxiety than others. The second hypothesis is that high school students choosing to pursue medicine at a higher education level have greater levels of mathematics anxiety than pedagogy, finance-economics, social sciences, natural sciences, engineering industry, information technology, transportation sectors and others. The third hypothesis is that female high school students suffer more mathematics anxiety than male students. The fourth hypothesis is that students in Grade 11 and Grade 12 attaining an average mathematics score 9.0–10.0 experienced higher levels of mathematics anxiety than others from the same school years. The fifth hypothesis is that positive coping strategies would be positively correlated with mathematics anxiety. The final hypothesis is that average mathematics score would be positively correlated with the levels of mathematics anxiety.

## 2 MATERIALS AND METHODS

### 2.1 Participants

A recruitment process was undertaken to ensure that all the high school students participating in the research did so voluntarily. The sampling frames for the respondents were obtained from nine high schools in two city regions and three provinces in Vietnam. A total of 1,691 questionnaires were distributed, all of which were returned. The authors eliminated 143 responses that were incomplete or contained insufficient information; the final sample size was 1,548. The sample consisted of 513 10th graders (33.1%), 462 11th graders (29.8%), and 573 12th graders (37.0%); with 570 males (36.8%) and 978 females (63.2%). An overview of the socio-demographic characteristics of subjects is shown in **Table 1**.

**TABLE 1** | Socio-demographic characteristics of subjects ($N$ = 1,548).

| | Participants |
|---|---|
| Gender | |
| Male, *n* (%) | 570 (36.8) |
| Female, *n* (%) | 978 (63.2) |
| Area | |
| Ho Chi Minh City, *n* (%) | 862 (55.7) |
| Khanh Hoa Province, *n* (%) | 110 (7.1) |
| Da Nang Province, *n* (%) | 366 (23.6) |
| Thua Thien Hue Province, *n* (%) | 91 (5.9) |
| Ha Noi Capital, *n* (%) | 119 (7.7) |
| Grade | |
| Grade 10, *n* (%) | 513 (33.1) |
| Grade 11, *n* (%) | 462 (29.8) |
| Grade 12, *n* (%) | 573 (37.0) |
| Average Mathematics Score | |
| <5.0, *n* (%) | 63 (4.1) |
| 5.0–6.0, *n* (%) | 195 (12.6) |
| 6.0–7.0, *n* (%) | 356 (23.0) |
| 7.0–8.0, *n* (%) | 464 (30.0) |
| 8.0–9.0, *n* (%) | 347 (22.4) |
| 9.0–10.0, *n* (%) | 347 (22.4) |
| Career Choice | |
| Pedagogy, *n* (%) | 239 (15.4) |
| Finance—Economics, *n* (%) | 403 (26.0) |
| Social Sciences, *n* (%) | 162 (10.5) |
| Natural Sciences, *n* (%) | 158 (10.2) |
| Engineering—Industry, *n* (%) | 180 (11.6) |
| Information Technology (IT), *n* (%) | 152 (9.8) |
| Transportation Sector, *n* (%) | 72 (4.7) |
| Medicine, *n* (%) | 129 (8.3) |
| Others, *n* (%) | 53 (3.4) |

*n: Number of participants.*

### 2.2 Instrument and Procedures

#### 2.2.1 Instrument

RMARS is a revised version of the original scale devised by Richardson and Suinn (1972); the measurement has 24 items and includes two aspects of mathematics anxiety measured by two subscales:

1) LMA is measured by 16 items and examines the anxiety caused by activities or processes of learning mathematics or statistics (a sample item is: "watching a teacher work an algebraic equation on the blackboard").
2) MEA is measured by 8 items and examines the anxiety caused by the assessment of mathematics or statistical learning process (a sample item is: "waiting to get a mathematics test returned in which you expected to do well").

RMARS is based on a 5-point Likert scale, which was used for all items, ranging from one to five (1 = never; 2 = rarely; 3 =

sometimes; 4 = regularly; 5 = always). Guidance for participants was provided at the top of the form.

Malhotra and Birks (2007) reported a method for ranking discrete values, as follows: (Maximum—Minimum)/$n$ = (5–1)/5 = 0.8. Based on this method, the rankings used were never (1.00–1.80), rarely (1.81–2.60), sometimes (2.61–3.40), regularly (3.41–4.20) and always (4.21–5.00). In our total sample, Cronbach's alpha was 0.788. This value shows that the scale is significant and reliable.

The ACI was developed by Tero and Connell (1984) to assess students' coping strategies in academic contexts. The measurement is based on 13 items addressing four academic coping strategies: 1) positive coping comprises three items measuring adaptive strategies when students have poor experiences with mathematics; 2) projective coping comprises three items rating the extent to which students blame others for their problems; 3) denial coping comprises three items examining whether students downplay the importance of negative events or ignore failures in mathematics; and 4) non-coping comprises four items assessing whether students blame themselves for their failures in mathematics or worry about what others think of their mistakes. In our sample, Cronbach's alpha was 0.647, indicating that the scale is significant and reliable.

### 2.2.2 Procedures

An informed consent process was used and participation was completely voluntary; respondents could withdraw at any time and would not be penalised. For the questionnaires, the participants were informed of the research aims and asked to provide their age, gender, school, average mathematics score, residence location, and career choices. The students then completed the self-report information, with researchers present to help the students and ensure that the questionnaires were completed correctly. It took 3 months to collect the data as part of an 8-month research project, from October 2020 to May 2021.

The 24-item RMARS was translated for Vietnamese students. Firstly, we translated and validated the scale with permission from the author to use it in our research project. We then invited a native speaker of Vietnamese, who is fluent in English, familiar with the culture, and has a research background with experience of translation, to help with the translation exercise.

A Vietnamese native speaker translator created a forward translation of the scale. Then, the initial Vietnamese translation was reconciled by all members of the research group to agree the ultimate translation for backward translation.

The back-translation from Vietnamese to English was conducted by a professional translator (native speaker of English and fluent in Vietnamese) with no information on the initial scale. Ultimately, the analysis group compared the backward translation to the original to determine whether there were any significant differences or discrepancies.

Finally, further verification of the 24-item RMARS was performed with a group of 20 people to ensure there were no issues in the interpretation of the scale. After investigating the results of applying the scale, no problems arose and the final Vietnamese version of RMARS was formally adopted.

### 2.2.3 Data Analysis

A multivariate analysis of variance (MANOVA) test used to determine significant differences between mathematics anxiety and the independent variables (gender, grade, career orientation, and academic achievement). Pearson correlation was conducted to establish the relationship between mathematics anxiety, academic coping strategies, and independent variables. Multiple linear regression analysis was used to examine the relationship between the predictor variables (academic coping strategies, gender, grade) and the dependent variable (mathematics anxiety).

# 3 RESULT

## 3.1 Factorial Validity

The data were analyzed by using Analysis of Moment Structures (AMOS) version 20.0. The two-factor model of the 24-item RMARS, which included the LMA and MEA subscales, was evaluated using confirmatory factor analysis (CFA) (Plake and Parker, 1982) with the most widely used model fit indices:

- RMSEA (root mean square error of approximation). A value of RMSEA ≤0.08 shows a good fit and between 0.08 and 0.10 provides a mediocre fit (MacCallum et al., 1996). The RMSEA value of 0.05 indicates a good fit, RMSEA 90% confidence interval (0.047, 0.053), $p < 0.001$.
- GFI (goodness-of-fit index). A value of GFI ≥0.90 is considered a good model fit and GFI ≥0.95 was considered a well fit (Hair et al., 2018). In the present research, the GFI value was 0.94, which was higher than 0.90 and could be considered a good model fit.
- CFI (comparative fit index). The CFI value was 0.868, which is smaller than the standard value of 0.90 and this was not acceptable.
- TLI (Tucker-Lewis index). A value of TLI ≥0.90 is a good model fit and ≥0.95 is a well-fit (Bentler and Bonett, 1980; Sharma et al., 2005). The TLI value was 0.841, which was not fit.

The appropriate fit indices RMSEA and GFI imply that the two-factor model is a good fit with the data. The measurement model should meet the criteria for the goodness of fit so that further analysis can be undertaken (Halim et al., 2018).

CMIN/DF is a calculation of the chi-square ($\chi 2$) value divided by the degree of freedom. A value of CMIN/DF ≤ 2.00 shows a good model fit and CMIN/DF ≤ 5.00 shows an acceptable fit (Hair et al., 2018). CMIN/DF value was 4.815 and could be considered an acceptable fit.

## 3.2 Construct Validity

The value of Average Variance Extracted (AVE) was 0.151, which was under 0.5. Therefore, in the case of AVE was less than 0.5 but the composite reliability value in this study was 0.784, which was higher than 0.6, the convergent validity was still adequate (Fornell and Larcker, 1981). Discriminant validity was acceptable by

**TABLE 2 |** Descriptive statistics of mathematics anxiety.

| Gender | Grade group | | | |
|---|---|---|---|---|
| | Grade 10 | Grade 11 | Grade 12 | Combined |
| Males (N) | 213 | 158 | 199 | 570 |
| LMA | | | | |
| M | 3.34 | 3.36 | 3.44 | 3.38 |
| SD | 0.49 | 0.49 | 0.46 | 0.48 |
| MEA | | | | |
| M | 3.35 | 3.28 | 3.41 | 3.35 |
| SD | 0.52 | 0.56 | 0.52 | 0.53 |
| Females (N) | 300 | 304 | 374 | 978 |
| LMA | | | | |
| M | 3.29 | 3.29 | 3.35 | 3.31 |
| SD | 0.42 | 0.52 | 0.46 | 0.47 |
| MEA | | | | |
| M | 3.36 | 3.23 | 3.4 | 3.34 |
| SD | 0.5 | 0.53 | 0.52 | 0.52 |

**TABLE 3 |** Correlation between LMA and MEA.

| | | LMA | MEA |
|---|---|---|---|
| LMA | Pearson Correlation | — | |
| | Sig. (2-tailed) | | |
| | N | 1548 | |
| MEA | Pearson Correlation | 0.576[a] | — |
| | Sig. (2-tailed) | 0 | |
| | N | 1,548 | 1,548 |

[a]*Correlation is significant at the 0.01 level (2-tailed).*

Fornell and Larcker (1981) criterion. To evaluate discriminant validity, the AVE may be compared with the square of the correlations among the latent variables (Chin, 1998). The Average Variance Extracted (AVE) estimated for the two factors (LMA & MEA) was 0.162 (LMA) and 0.129 (MEA), which were lower than the square of the correlation between the two factors to provide evidence of discriminant validity which was 0.759.

## 3.3 Reliability

With a two-factor model of the 24-item RMARS, the study assessed the internal consistency of subscales using Cronbach's Alpha (Cronbach, 1951) and Composite Reliability (Wasko and Faraj, 2005). The values of Cronbach's alpha in this study were 0.81 (LMA) and 0.67 (MEA). Although Cronbach's alpha should be higher than 0.70 to ensure the reliability of the scale, values below 0.70 are still acceptable (Hair et al., 2007; Taber, 2018). The CR value of LMA was 0.725, which was higher than the recommended value of 0.7 (Fornell and Larcker, 1981) and the CR value of MEA was 0.505, which was lower than the recommended value. The CR of the 24-item RMARS was 0.784. Therefore, the variables in this study were considered reliable.

## 3.4 Descriptive Analysis

According to the norms for RMARS (Plake and Parker, 1982), the participants scored in the average range on the mathematics anxiety scale, with a mean of 3.34 (SD = 0.47) for the LMA subscale and 3.34 (SD = 0.52) for the MEA subscale. **Table 2** shows descriptive statistics of the dependent variables, including LMA and MEA results by gender and grade level groups.

## 3.5 Inferential Analysis

A MANOVA was performed with gender, grade, career choices and average mathematics score as independent variables, and the LMA and MEA subscales as dependent variables. To run MANOVA, the researchers conducted a preliminary analysis to examine the absence of multicollinearity and homogeneity of covariance matrices. Pearson correlations were performed between two dependent variables to test the MANOVA assumption that dependent variables would be moderately correlated with each other (Meyers et al., 2016). The correlation value r should not be greater than 0.90 (Tabachnick et al., 2007). As can be seen in **Table 3**, a meaningful pattern of correlations was observed amongst the two dependent variables, suggesting the appropriateness of using MANOVA.

The multivariate homogeneity of covariance matrices was examined using Box's M test; the M value of 861.630 was not significant ($p < 0.001$), hence the assumption of homogeneity of covariance matrices was not met. As a result, Pillai's trace value, a more robust statistic, was used to confirm the result.

A separate two-way univariate analysis of variance (ANOVA) for each of the dependent variables was conducted (**Table 4**). Levene's test of equality of error variances was used to test the assumption from the MANOVA and ANOVA that the variances for each variable are equal across the groups. If Levene's test is significant, this means that the assumption has not been satisfied. In this study, the value of Levene's test came out to be significant for all the variables in the LMA subscale [F (278, 1269) = 1.68, $p < 0.05$], and MEA subscales [F (278, 1269) = 1.459, $p < 0.05$]. Therefore, when the follow-up ANOVAs were conducted, the results for LMA and MEA were interpreted with caution. A test of the standard deviations reported that none of the largest standard deviations was more than four times the size of the corresponding smallest, suggesting that the ANOVA was robust (Howell, 2007).

There was a significant difference in the level of mathematics anxiety between Grades 10, 11 and 12 when jointly considering LMA and MEA variables, Pillai's trace value = 0.01; F(4, 2538) = 3.051, $p = 0.016$, partial η2 = 0.005. Therefore, the results suggest that the first hypothesis (H1) should be rejected. A separate ANOVA was conducted for each dependent variable, with each ANOVA evaluated at an alpha level of 0.025 (that is, 0.05/2). There was a significant difference between Grades 10, 11 and 12 for MEA; F(2, 1269) = 3.861, $p = 0.021$, partial η2 = 0.006, with Grade 12 (M = 3.34, SD = 0.03) scoring higher than Grade 11 (M = 3.23, SD = 0.03) and Grade 10 (M = 3.29, SD = 0.03). There was no significant difference between Grades 10, 11 and 12 for LMA; F(2, 1269) = 3.121, $p = 0.044$, partial η2 = 0.005.

There was a significant difference in the level of mathematics anxiety according to career choice; Pillai's trace = 0.211, F(16, 2538) = 18.708, $p = 0.000$, partial η2 = 0.105. Therefore, the results suggest that the second hypothesis (H2) should be rejected. A separate ANOVA was conducted for each dependent variable. There was a significant difference between students' career

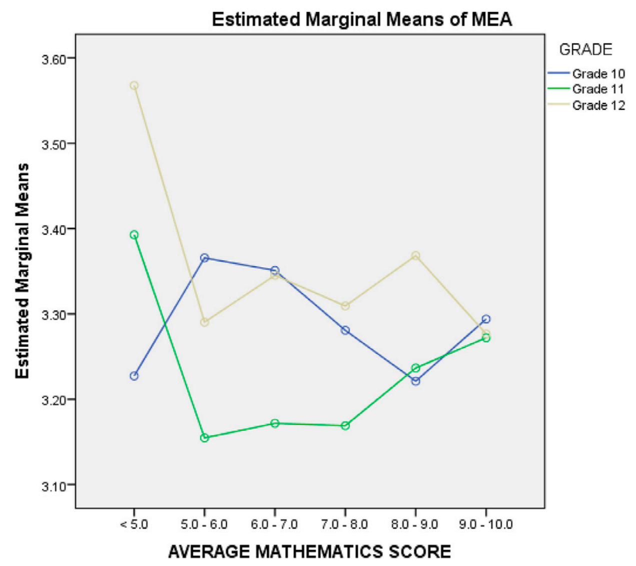


**FIGURE 1 |** Interaction plot.

choices in terms of LMA; F(8, 1269) = 36.760, $p$ = 0.000, partial η2 = 0.188. Students choosing finance-economics (M = 3.53, SD = 0.03), or industrial engineering (M = 3.53, SD = 0.04) experienced higher levels of LMA than others. There was a significant difference between students' career choices on MEA; F(8, 1269) = 14.379, $p$ = 0.000, partial η2 = 0.083. Students choosing finance-economics (M = 3.50, SD = 0.04) experienced higher levels of MEA than others.

There was no significant difference in the level of mathematics anxiety between male and female students in terms of LMA and MEA; Pillai's trace value = 0.003; F(2, 1268) = 1.950, $p$ = 0.143, partial η2 = 0.003. Therefore, the results suggest that the third hypothesis (H3) should be rejected. With MEA, male students (M = 3.3, SD = 0.03) scored slightly higher than female students (M = 3.27, SD = 0.02). With LMA, male students (M = 3.3, SD = 0.02) scored slightly higher than female students (M = 3.22, SD = 0.02). However, these differences is statistically non-significant.

The results reveal that there is a significant multivariate effect on LMA and MEA in the interaction between grade level and students' average mathematics scores; Pillai's trace = 0.026, F(20, 2538) = 1.664, $p$ = 0.032, partial η2 = 0.013. Therefore, the results suggest that the fifth hypothesis (Ho5) should be rejected. A separate ANOVA was conducted for each dependent variable. There was a significant difference between grade level and students' average mathematics scores on MEA; F(10, 1269) = 2.251, $p$ = 0.015, partial η2 = 0.017. By looking at the interaction plots (**Figure 1**), students in Grade 11 (M = 3.39, SD = 0.11) and Grade 12 (M = 3.57, SD = 0.15) getting average mathematics scores below 5.0 had higher levels of MEA than others from the same school years. In Grade 10, students getting average mathematics scores 5.0–6.0 (M = 3.37, SD = 0.08) had higher levels of MEA than others from the same school years. The mean scores of students in MEA are presented in **Table 5**. There was no significant difference on LMA; F(10, 1269) = 1,868, $p$ = 0.056, partial η2 = 0.015.

## 3.6 Correlation

**Table 6** shows how mathematics anxiety correlates with academic coping strategies, average mathematics scores, and gender. The results are significant, with a moderately positive correlation between mathematics anxiety and positive coping (r = 0.487, $p < 0.01$); a weak positive correlation between mathematics anxiety and non-coping (r = 0.213, $p < 0.01$); gender (r = 0.050, $p < 0.05$); and average mathematics score (r = 0.064, $p < 0.05$). This finding shows that students with higher levels of positive coping and non-coping suffer mathematics anxiety to

**TABLE 4 |** The mean scores of students in MEA.

| Dependent Variable | GRADE | AVERAGE MATHEMATICS SCORE | Mean | Std. Error | 95% Confidence Interval | |
|---|---|---|---|---|---|---|
| | | | | | Lower Bound | Upper Bound |
| MEA | Grade 10 | <5.0 | 3.227[a] | 0.125 | 2.982 | 3.473 |
| | | 5.0–6.0 | 3.366[a] | 0.077 | 3.216 | 3.516 |
| | | 6.0–7.0 | 3.351 | 0.066 | 3.221 | 3.481 |
| | | 7.0–8.0 | 3.281 | 0.057 | 3.169 | 3.393 |
| | | 8.0–9.0 | 3.221 | 0.055 | 3.114 | 3.329 |
| | | 9.0–10.0 | 3.294[a] | 0.082 | 3.134 | 3.454 |
| | Grade 11 | <5.0 | 3.393[a] | 0.105 | 3.186 | 3.599 |
| | | 5.0–6.0 | 3.155[a] | 0.079 | 3.000 | 3.310 |
| | | 6.0–7.0 | 3.172[a] | 0.059 | 3.056 | 3.288 |
| | | 7.0–8.0 | 3.169 | 0.064 | 3.043 | 3.295 |
| | | 8.0–9.0 | 3.237[a] | 0.060 | 3.119 | 3.354 |
| | | 9.0–10.0 | 3.272[a] | 0.104 | 3.067 | 3.477 |
| | Grade 12 | <5.0 | 3.568[a] | 0.146 | 3.281 | 3.855 |
| | | 5.0–6.0 | 3.290[a] | 0.087 | 3.119 | 3.462 |
| | | 6.0–7.0 | 3.345[a] | 0.059 | 3.229 | 3.461 |
| | | 7.0–8.0 | 3.309 | 0.056 | 3.199 | 3.420 |
| | | 8.0–9.0 | 3.368 | 0.059 | 3.252 | 3.485 |
| | | 9.0–10.0 | 3.276[a] | 0.108 | 3.064 | 3.489 |

[a]*Based on modified population marginal mean.*

**TABLE 5 |** Combined univariate ANOVA.

| Source | Dependent Variable | Type III Sum of Squares | df | Mean Square | F | Sig | Partial Eta Squared |
|---|---|---|---|---|---|---|---|
| Corrected | LMA | 144.587[a] | 278 | 0.520 | 3.233 | 0.000 | 0.415 |
| Model | MEA | 124.075[b] | 278 | 0.446 | 1.881 | 0.000 | 0.292 |
| Intercept | LMA | 5277.582 | 1 | 5277.582 | 32802.285 | 0.000 | 0.963 |
| | MEA | 5421.941 | 1 | 5421.941 | 22848.655 | 0.000 | 0.947 |
| GENDER | LMA | 0.592 | 1 | 0.592 | 3.679 | 0.055 | 0.003 |
| | MEA | 0.452 | 1 | 0.452 | 1.907 | 0.168 | 0.002 |
| GRADE | LMA | 1.004 | 2 | 0.502 | 3.121 | 0.044 | 0.005 |
| | MEA | 1.832 | 2 | 0.916 | 3.861 | 0.021 | 0.006 |
| AMS | LMA | 2.409 | 5 | 0.482 | 2.995 | 0.011 | 0.012 |
| | MEA | 1.497 | 5 | 0.299 | 1.262 | 0.278 | 0.005 |
| CAREER | LMA | 47.315 | 8 | 5.914 | 36.760 | 0.000 | 0.188 |
| | MEA | 27.296 | 8 | 3.412 | 14.379 | 0.000 | 0.083 |
| GENDER * GRADE | LMA | 0.999 | 2 | 0.499 | 3.105 | 0.045 | 0.005 |
| | MEA | 1.416 | 2 | 0.708 | 2.984 | 0.051 | 0.005 |
| GENDER * AMS | LMA | 1.280 | 5 | 0.256 | 1.591 | 0.159 | 0.006 |
| | MEA | 0.738 | 5 | 0.148 | 0.622 | 0.683 | 0.002 |
| GENDER * CAREER | LMA | 1.645 | 8 | 0.206 | 1.278 | 0.251 | 0.008 |
| | MEA | 1.114 | 8 | 0.139 | 0.587 | 0.790 | 0.004 |
| GRADE * AMS | LMA | 3.006 | 10 | 0.301 | 1.868 | 0.046 | 0.015 |
| | MEA | 5.257 | 10 | 0.526 | 2.215 | 0.015 | 0.017 |
| GRADE * CAREER | LMA | 3.520 | 16 | 0.220 | 1.368 | 0.149 | 0.017 |
| | MEA | 4.080 | 16 | 0.255 | 1.075 | 0.375 | 0.013 |
| AMS * CAREER | LMA | 8.932 | 40 | 0.223 | 1.388 | 0.056 | 0.042 |
| | MEA | 11.096 | 40 | 0.277 | 1.169 | 0.219 | 0.036 |
| GENDER * GRADE * AMS | LMA | 1.530 | 10 | 0.153 | 0.951 | 0.485 | 0.007 |
| | MEA | 1.649 | 10 | 0.165 | 0.695 | 0.730 | 0.005 |
| GENDER * GRADE * CAREER | LMA | 3.385 | 16 | 0.212 | 1.315 | 0.179 | 0.016 |
| | MEA | 6.590 | 16 | 0.412 | 1.736 | 0.035 | 0.021 |
| GENDER * AMS * CAREER | LMA | 7.073 | 37 | 0.191 | 1.188 | 0.205 | 0.033 |
| | MEA | 17.802 | 37 | 0.481 | 2.028 | 0.000 | 0.056 |
| GRADE * AMS * CAREER | LMA | 11.481 | 68 | 0.169 | 1.049 | 0.371 | 0.053 |
| | MEA | 21.529 | 68 | 0.317 | 1.334 | 0.039 | 0.067 |
| GENDER * GRADE * AMS * CAREER | LMA | 6.959 | 50 | 0.139 | 0.865 | 0.736 | 0.033 |
| | MEA | 12.674 | 50 | 0.253 | 1.068 | 0.349 | 0.040 |
| Error | LMA | 204.170 | 1269 | 0.161 | | | |
| | MEA | 301.131 | 1269 | 0.237 | | | |
| Total | LMA | 17592.535 | 1548 | | | | |
| | MEA | 17741.234 | 1548 | | | | |
| Corrected Total | LMA | 348.757 | 1547 | | | | |
| | MEA | 425.206 | 1547 | | | | |

[a]*R Squared = 0.415 (Adjusted R Squared = 0.286).*
[b]*R Squared = 0.292 (Adjusted R Squared = 0.137).*
*Note: AMS: Average Mathematics Score.*

**TABLE 6 |** Correlation.

| | *MA* | *PC* | *PRC* | *DC* | *NC* | *AMS* | *GENDER* |
|---|---|---|---|---|---|---|---|
| MA | | | | | | | |
| PC | 0.487[a] | | | | | | |
| PRC | 0.010 | −0.117[a] | | | | | |
| DC | −0.131[a] | −0.254[a] | 0.333[a] | | | | |
| NC | 0.213[a] | 0.221[a] | 0.121[a] | −0.130[a] | | | |
| AMS | 0.064[b] | 0.179[a] | −0.098[a] | −0.080[a] | −0.115[a] | | |
| GENDER | 0.050[b] | −0.028 | 0.017 | 0.082[a] | −0.127[a] | 0.041 | |

[a]*Correlation is significant at the 0.01 level (2-tailed).*
[b]*Correlation is significant at the 0.05 level (2-tailed).*
*Note: MA: Mathematics Anxiety; PC: Positive Coping; PRC: Projective Coping; DC: Denial Coping; NC: Non-Coping; AMS: Average Mathematics Score.*

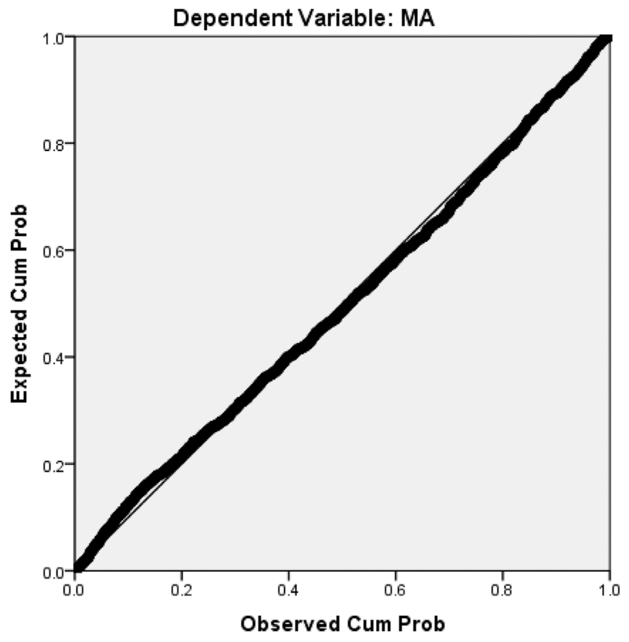


**FIGURE 2** | Normal P-P-plot of the regression standardised residual.

a greater extent than others. In addition, the higher the mathematics anxiety level, the higher the average mathematics score. There was a significant, weak negative correlation between mathematics anxiety and denial coping (r = −0.131, $p < 0.01$), indicating that the higher the level of denial coping, the lower the level of mathematics anxiety and vice versa. Mathematics anxiety was not significantly correlated with projective coping strategies.

## 3.7 Regression

Multiple linear regression analysis was used to determine the factors influencing level of mathematics anxiety among high school students. Multiple linear regression analysis was performed with the following independent variables: academic coping strategies, including positive coping, projective coping, denial coping, and non-coping; students' average mathematics score; gender; grade; and career choice. The dependent variable was the mathematics anxiety scale. The preliminary assumption of multiple linear regression was used as the basis for examining multicollinearity. Additionally, the normal P-P plot of the regression standardised residuals shows that the scattered points are principally distributed on the diagonal, which suggests that the residuals could be judged to be normally distributed, as presented in **Figure 2**.

Multicollinearity was examined for all independent variables using Pearson's bivariate correlation. The correlation coefficients were less than 0.8, indicating that there was no multicollinearity between the independent variables (Allison, 1999). The variance inflation factor (VIF) and tolerance value were determined to test this assumption. The tolerance of every variable was higher than 0.1 and the VIF values for all variables were lower than 10, indicating that there was no multicollinearity between the independent variables in the multiple regression analysis (Uyanık and Güler, 2013). Therefore, the assumption was satisfied and the regression analysis was conducted.

**Table 7** reveals that the corrected coefficient, Adjusted R2, was 0.384, indicating a change in the dependent variable, students' mathematics anxiety, due to a one-unit change in the independent variable. The regression model was statistically significant (F(18, 1529) = 54.658, $p < 0.001$, R2 = 0.392). The results of the multiple regressions with independent factors regressed against students' mathematics anxiety show that positive coping (β = 0.198, $p < 0.001$), projective coping (β = 0.032, $p < 0.05$), non-coping (β = 0.036, $p < 0.001$), gender (β = 0.066, $p < 0.05$), grade and career choices were significant predictors in the model.

Specifically, the difference in mathematics anxiety between grade 10 and grade 12 was −0.034. The difference in mathematics anxiety between grade 11 and grade 12 was −0.037. According to career choices, the difference in mathematics anxiety between Pedagogy students and others was 0.488. The difference in mathematics anxiety between Finance—Economics students and others was 0.672. The difference in mathematics anxiety between Social Sciences students and other students was 0.613. The difference in mathematics anxiety between Natural Sciences students and others was 0.484. The difference in mathematics anxiety between Engineering—Industry students and others was 0.725. The difference in mathematics anxiety between Information Technology (IT) students and others was 0.553. The difference in mathematics anxiety between Transportation Sector students and others was 0.136. The difference in mathematics anxiety between Medicine students and others was 0.578.

However, mathematics anxiety shows non-significant associations with average mathematics scores and denial coping strategies. Regression analysis showed that factors including positive coping, projective coping, non-coping, gender, grade, and students' future career choices are significant predictors of mathematics anxiety. When examining the interaction, results revealed non-significant interaction between grade and average mathematics scores in predicting mathematics anxiety among students.

# 4 DISCUSSION

The main aims of this research were twofold: firstly, to examine mathematics anxiety among Vietnamese high school students, and secondly, to test the correlation between students' mathematics anxiety and academic coping strategies.

The analysis was intriguing to the authors. It did not show any differences in mathematics anxiety between male and female high school students; this is a significant contribution to research on underlying gender differences in relation to mathematics anxiety. It was predicted that the findings would support the hypothesis that mathematics anxiety reduces the mathematics achievement of students; however, the fourth hypothesis was accepted. Although the result showed that there was a correlation between mathematics anxiety and mathematics achievement, mathematics anxiety had a non-significant effect on

**TABLE 7** | The results of multiple regression analysis of mathematics anxiety.

| Model | | Unstandardized Coefficients | | Standardized Coefficients | t | Sig. | F | R2 | Adjusted R2 |
|---|---|---|---|---|---|---|---|---|---|
| | | B | Std. Error | Beta | | | | | |
| 1 | (Constant) | 1.795 | 0.088 | | 20.482 | 0.000 | | | |
| | PC | 0.198 | 0.012 | 0.369 | 16.566 | 0.000 | | | |
| | PRC | 0.032 | 0.012 | 0.058 | 2.685 | 0.007 | | | |
| | DC | −0.009 | 0.011 | −0.018 | −0.807 | 0.420 | 54.658 | 0.392 | 0.384 |
| | NC | 0.036 | 0.009 | 0.087 | 4.060 | 0.000 | | | |
| | AMS | 0.002 | 0.013 | 0.007 | 0.191 | 0.849 | | | |
| | GENDER | 0.066 | 0.019 | 0.072 | 3.472 | 0.001 | | | |
| | GRADE10 | −0.034 | 0.069 | −0.036 | −0.485 | 0.628 | | | |
| | GRADE11 | −0.037 | 0.069 | −0.038 | −0.528 | 0.598 | | | |
| | Pedagogy | 0.488 | 0.053 | 0.400 | 9.158 | 0.000 | | | |
| | Finance_Economics | 0.672 | 0.052 | 0.671 | 13.053 | 0.000 | | | |
| | NaturalScience | 0.484 | 0.055 | 0.332 | 8.730 | 0.000 | | | |
| | SocialSciences | 0.613 | 0.056 | 0.426 | 11.001 | 0.000 | | | |
| | Engineering_Industry | 0.725 | 0.055 | 0.527 | 13.127 | 0.000 | | | |
| | InformationTechnology | 0.553 | 0.056 | 0.373 | 9.814 | 0.000 | | | |
| | TransportationSector | 0.136 | 0.063 | 0.063 | 2.140 | 0.033 | | | |
| | Medicine | 0.578 | 0.057 | 0.362 | 10.105 | 0.000 | | | |
| | GRADE10*AMS | −0.008 | 0.017 | −0.034 | −0.438 | 0.661 | | | |
| | GRADE11*AMS | −0.004 | 0.018 | −0.015 | −0.208 | 0.835 | | | |

mathematics achievement. The other important finding is that the more students suffer from mathematics anxiety, the more they adopt positive coping strategies.

These findings reinforce the general belief that students in Grade 12 suffer more from mathematics anxiety than those in Grades 10 and 11. The education curriculum in high school, especially in Grade 12, includes demanding academic tasks and complex academic content that give rise to academic pressure. Moreover, Grade 12 students have to pass a graduation examination to enroll in their desired university. Academic pressure can also be a consequence of parental pressure (Deb et al., 2015), which impacts students' mental health and leads to psychological problems related to mathematics anxiety. Our results do not show any significant correlation that contradicts the findings of Lew and Hwang (2019), who reported that Grade 11 students had the highest level of mathematics anxiety and Grade 12 students the lowest. Another study found that there is no significant difference in the levels of mathematics anxiety between grades (Luo et al., 2009).

This study shows that students choosing to pursue finance-economics or industrial engineering at a higher education level have greater levels of mathematics anxiety than others. This finding is in contrast with previous studies and can be explained in a number of ways. Chipman et al. (1992) reported that students with mathematics anxiety were likely to choose degree courses with the minimum requirements for knowledge related to mathematics, such as the arts and humanities, languages, politics, and psychology and sociology, instead of courses such as natural science and economics (Zettle and Raines, 2000). Finance-economics and industrial engineering are popular specialties requiring substantial mathematics knowledge. Moreover, one of the most important criteria for applying to these courses, is the score in the entrance examination, which has gradually risen each year in Vietnam. This rise could be interpreted in two ways: 1) higher levels of competence are needed for career choices, for instance, international collaboration, multidisciplinary knowledge, and subject knowledge (Tran et al., 2016); and 2) the number of students applying to finance-economics and industrial engineering courses has gradually increased which has led to greater competition. The higher level of mathematics anxiety among students pursuing finance-economics and industrial engineering may be a direct consequence of the increasing score requirement.

Gender differences in mathematics anxiety have been thoroughly studied and well documented. Specifically, mathematics anxiety has been found to be significantly higher in female students than in male students (Karimi and Venkatesan, 2009; Luo et al., 2009; Cheema and Sheridan, 2015; Lew and Hwang, 2019). However, when comparing our results to those of previous studies, the results run counter to the way in which gender difference has been debated in the fields of psychology and educational science. Several studies have found results that are consistent with our reported findings. Keshavarzi and Ahmadi (2013), and Akbayir (2019), also found no difference between male and female high school students in levels of mathematics anxiety. Until now, gender differences in mathematics anxiety have been assumed to be influenced by factors such as a student's attraction to the mathematics field (Keshavarzi and Ahmadi, 2013); the possibility that females are more willing to disclose anxiety(Ashcraft, 2002); social stereotypes about women and mathematical abilities (Beilock et al., 2007); spatial processing ability (Maloney and Beilock, 2012); and gender differences in stress reactivity (Altemus et al., 2014). In modern Vietnamese society, underestimation of the success of females in mathematics has been transmuted into respect for their abilities and achievements. This alteration in the Vietnamese context has contributed to removing gender stereotypes and increased self-confidence among females. Thus, female anxiety has decreased. Our findings on gender differences in mathematics anxiety could be explained by this shift.

The present research found an interaction between grade level and students' academic achievement. Specifically, students in Grade 11 and Grade 12 attaining an average score below 5.0 experienced higher levels of MEA than others from the same school years. This finding shows that students with low average scores are likely to experience greater anxiety associated with a mathematical examination or test. In the Vietnamese educational context, tests, and examinations in compulsory education, especially in high school, are widely regarded as an essential and effective tool for evaluating personal qualities. Therefore, low and poor scores lead to negative feelings, such as disappointment, embarrassment, irritation, stress and anxiety. This finding is very similar to results that have been previously reported. For example, Nicholson (2009) found that the academic achievement of Grade 11 students is negatively affected by anxiety related to tests. Another study, conducted by Karatas et al. (2013), found that the more test anxiety that students experienced, the poorer their score in university entrance examinations. Additionally, grade point averages could be affected by high levels of test anxiety (Whitaker Sena et al., 2007; Von Der Embse et al., 2013). Tests and examinations have negative effects not only on students' academic achievement but also on their health (Zeidner, 1998). Moreover, this anxiety is a factor inhibiting students from achieving their academic goals and demonstrating their full potential in the learning process (Zoller and Ben-Chaim, 1990).

Our data analysis reveals that there is a positive correlation between the level of mathematics anxiety and mathematics achievement among students. The result shows that individuals who have high levels of mathematics anxiety tend to have higher average scores in mathematics. Specifically, students attaining averages from 9.0 to 10.0 experience greater LMA than others. This is an interesting finding, as it is contrary to what we know from previous studies (Karimi and Venkatesan, 2009; Lew and Hwang, 2019; Milovanović, 2020), which have reported a significant negative correlation between mathematics anxiety and mathematics achievement. However, few previous studies have been conducted to explain the negative relationship between mathematics anxiety and mathematics achievement. This relationship could be associated with reduced student effort and comprehension in the learning process; reduced accomplishment of study goals (Lew and Hwang, 2019); low mathematics ability (Tobias, 1986; Hembree, 1990; Ma and Xu, 2004); and students' understanding and self-confidence in mathematics (Zakaria et al., 2012). For a long time in the Vietnamese educational context, grade point averages were considered to be the standard for evaluating whether students accomplished academic goals and gained academic achievements. Specifically, mathematics is an important subject for all students in the educational system and a compulsory subject in entrance and graduation exams. This situation increased students' determination to complete mathematics-related tasks and attain better performance in the field of mathematics. The higher the average score attained by a student, the greater their interest in education, and this led to anxiety about mathematics among students. Our views on the association between mathematics anxiety and mathematics achievement can be clarified by these explanations.

The relation between positive coping strategies and mathematics anxiety has been examined in detail in the studies mentioned. In particular, mathematics anxiety has been found to be negatively correlated with positive coping strategies. The higher the levels of mathematics anxiety that students experience, the less likely they are to adopt positive coping strategies (Skaalvik, 2018). The findings from the present study are the reverse. Our findings show that there is a positive relationship between mathematics anxiety and positive coping strategies among students. For decades, traditional education in Vietnam has created a favourable learning environment for enhancing students' knowledge, self-regulated learning ability, academic self-concept, motivation, and coping strategies. Several prior studies have examined academic motivation and self-regulated learning affecting the learning process of students; for instance, encouraging students to engage in learning-related tasks more efficiently (Zeynali et al., 2019), and proactively managing students' learning environment (Pintrich, 1999). Salomon and Ket (2007) reported that Vietnamese society is influenced by Confucian traditions. Specifically, the academic self-concept is considered particularly important in Vietnam's education system, placing a strong emphasis on students' willingness to persevere and their working hard. For these reasons, when students face academic challenges, obstacles and difficulties in mathematics, they tend to focus on solving problems rather than blaming others for their mistakes or ignoring negative events. Therefore, the higher the level of mathematics anxiety that students experience, the more likely they are to adopt positive coping, understanding their mistakes and working out how to do better the next time.

## 4.1 Limitations

This study has several limitations. The first is that participants were not distributed uniformly; specifically, female participants outnumbered male participants by a proportion of approximately two to one, and this may affect the inaccuracy of the results. Therefore, future research should be conducted to validate the findings of this study. Also, only five factors were examined in researching the influences of mathematics anxiety in high school students. Thus, other factors, such as teacher attitude, classroom environment, learning programs and teaching methods could be included in future investigations.

## 5 CONCLUSION AND IMPLICATIONS

Mathematics anxiety is an unpleasant emotional state, with tension and anxiety that affect the ability to manipulate numbers and participate in the mathematical learning process. This research makes a substantial contribution on the issue, as follows: 1) it highlights the effects of academic achievement and students' career choices on mathematics anxiety; 2) it provides additional evidence of non-significant effects of gender difference on mathematics anxiety; 3) it offers insights into academic coping strategies that students adopt to overcome mathematics anxiety.

Future research should be designed to study factors influencing the relationship between academic achievement, gender difference and mathematics anxiety in more depth. Additionally, further investigation is necessary to evaluate the significant impact of academic coping strategies on anxiety in the learning process.

Our study contributes to the general discussion about the relationship between mathematics anxiety and academic coping strategies (Skaalvik, 2018), grade (Lew and Hwang, 2019), academic achievement (Puteh and Khalin, 2016), and students' career choices (Chipman et al., 1992). Besides, the results are helpful for making students aware of mathematics anxiety, protecting themselves from mental illness such as stress, anxiety disorders and depression, and enhancing students' mental health during the learning process. From that, students could understand their mental health status and implement coping strategies to get over their academic anxiety. Our findings provide additional information for teachers, school counselors to realize student's negative emotions, opportunely support, and find appropriate methods to alleviate student's negative emotions during the teaching process (Asikhia et al., 2015; Olaoluwa, 2021). Moreover, educators can design mathematics curriculum integrating theories and practices, and develop psychological support programs for Vietnamese high school students (Van et al., 2019) such as organizing hands-on activities in mathematics learning, applying cooperative learning in small-group learning, providing extra tuition sessions, organizing more discussions activities and more student directed classroom, and focusing on individual mathematics improvement. It is also essential to create support groups about mathematics in school that students can share and socialize during the learning process.

## 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

V-LT-C contributed to conception and design of the study. H-TL-T, T-TN-T, M-TN-T, TT-L, and B-TN-D organized the database. T-TN-T and M-TN-T performed the statistical analysis. H-TL-T, T-TN-T, M-TN-T, TT-L, and B-TN-D wrote the first draft of the manuscript. All authors contributed to manuscript revision, read, and approved the submitted version.

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# Translating Embodied Cognition for Embodied Learning in the Classroom

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In this perspective piece, we briefly review embodied cognition and embodied learning. We then present a translational research model based on this research to inform teachers, educational psychologists, and practitioners on the benefits of embodied cognition and embodied learning for classroom applications. While many teachers already employ the body in teaching, especially in early schooling, many teachers' understandings of the science and benefits of sensorimotor engagement or embodied cognition across grades levels and the content areas is little understood. Here, we outline seven goals in our model and four major "action" steps. To address steps 1 and 2, we recap previously published reviews of the experimental evidence of embodied cognition (and embodied learning) research across multiple learning fields, with a focus on how both simple embodied learning activities—as well as those based on more sophisticated technologies of AR, VR, and mixed reality—are being vetted in the classroom. Step 3 of our model outlines how researchers, teachers, policy makers, and designers can work together to help translate this knowledge in support of these goals. In the final step (step 4), we extract generalized, practical embodied learning principles, which can be easily adopted by teachers in the classroom without extensive training. We end with a call for educators and policy makers to use these principles to identify learning objectives and outcomes, as well as track outcomes to assess whether program objectives and competency requirements are met.

**Keywords: translational science, embodied cognition, teaching—learning, pedagogy, learning sciences**

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## *MINDING* THE (BRAIN) GAP

Currently, there is paradox in education: a focus on evidence-based research but an abandonment of the theories (Matsushita, 2017). For example, effective performance in clinical settings requires the integration between theory and practice. Yet there is a gap between theoretical knowledge as taught in the classroom and what K-12 students experience and learn (Hashemiparast et al., 2019). Furthermore, teachers' action-based classroom research, while often promoting student achievement, is often absent of robust links to theory and is liable to neglect the application of a deductive, empirical framework. One reason for this dearth of informed practice is a lack of a framework for translating theory to practice, and in this instance, linking embodied cognition and embodied learning to effective teaching.

To promote informed research-based decisions in education, the *No Child Left Behind* Act (2002) mandated "scientifically based" research, which was replaced by *Every Student Succeeds* Act (2015) calling for "evidence-based" interventions. Still, few educators are privy to the research advances in the science of learning (Weinstein et al., 2018). Further, the limited awareness of recent theoretical and empirical evidence in cognitive science constrains the dissemination and adoption of research findings. There is a need for collaborative models that emphasize a bidirectional flow from researchers to practitioners (Nutley et al., 2009). Indeed, McKenney (2018) notes: "Although many studies in the learning sciences describe potential implications of policy or practice, few elaborate on how recommendations can be implemented" (p. 1).

Specifically, as Wilcox et al. (2021) point out there continues to be a significant "research to practice gap". For example, Roediger (2013) writes:

> *We cannot point to a well-developed translational educational science in which research about learning and memory, thinking and reasoning, and related topics is moved from the lab into controlled field trials (like clinical trials in medicine) and the tested techniques … are introduced into broad educational practice. We are just not there yet …* (p. 1).

Furthermore, one of the nation's foremost education researchers and policy analysts, Linda Darling-Hammond, argues that the rapid pace of our knowledge of human development and learning has impacted the emerging consensus about the science of learning and increased our opportunities to shape more effective educational practices (Darling-Hammond et al., 2020). Yet, she adds, to take advantage of these advances requires integrating insights across multiple fields and connecting them to our knowledge of successful approaches.

In this perspective piece, we adapted a translational research model for the learning sciences to inform teachers, educational psychologists, and practitioners on benefits of Embodied Cognition (EC) and Embodied Learning (EL) applications for the classroom.

## TRANSLATIONAL SCIENCE: THE NEED FOR A BRIDGE

Translational science research emphasizes a need for appropriate professional development that fosters interdisciplinary approaches (Gilliland et al., 2017) for quickly turning biomedical findings from the laboratory, clinic, and community into interventions to improve the health of individuals and the public (NCATS-NIH, 2020). That said, to meet the challenges of collecting and disseminating the latest cognitive-science empirical research on learning, we adapted a model of translational science (Rubio et al., 2010). We call our model the *Translational Learning Sciences Research* for Embodied Cognition and Embodied Learning[1]. Our model leverages the empirical findings on EC from psychology and learning theory to provide an overarching theory for why embodied-based learning works. The call for translational research for the benefit of education is not new, although the term *translational* has only recently been applied in fields other than the natural sciences[2]. Here, we provide a framework for why these examples work and what generalized learning principles can be derived from these examples to impart educators with useful practice. Our model curates EC research across multiple learning fields (e.g., STEM, reading/language, social-emotional learning) while focusing on how researchers are beginning to implement both low-stakes embodied learning activities in the classroom and also those based on sophisticated technologies of AR, VR, and mixed reality (step 1 and 2 of our model). Our model then extracts generalized EL principles that can be easily used in the classroom as a starting point for researchers, teachers, policy makers, and designers to work together (step 3) to help translate and disseminate the latest research and create validated learning platforms and activities based on EC principles (step 4). The goal is to accelerate the process of transforming laboratory discoveries into new pedagogical approaches to improve learning outcomes. Before we discuss the details of our model, however, we present a quick history of EC and EL and why it matters to education.

### Rethinking Thinking

Over the last forty years there has been a paradigm shift in Psychology, in which human thinking is now viewed as inseparably linked with the body and the environment (e.g., Varela et al., 1991; Wilson, 2002; Abrahamson, 2004; Hutto, 2007; Chemero, 2009; Fugate et al., 2018). Embodied views of thinking suggest that it is deeply dependent on features of the physical body of the learner, where the body plays a significant causal or constitutive role in cognitive processing (Kumar, et al., 2018; Wilson and Foglia, 2011). Such embodied views of cognition are based on bodily and neural processes of perception, action, and emotion (e.g., Hauk et al., 2004; James, 2010; Vinci-Booher and James, 2020, to name a few). For example, research also shows that simply *observing* another's gestures and movements can activate the mirror neuron system in the learner's brain to aid in learning through imitation (Rizzolatti et al., 1996). This finding has led to the suggestion that the mirror neuron system may be the mechanism for imitative EC (Rizzolatti et al., 1996; Iacoboni et al., 2005; Iacoboni, 2009).

We owe a great deal to developmental psychologists whose theoretical insights are affirmed by the latest neuroscientific evidence (e.g., Piaget and Cook, 1952; Piaget, 1968; Montessori, 1969; Vygotsky, 1978; Kolb, 1984; Dewey, 1989; Rogoff, 1990). Indeed, Vygotsky (1926/1997) wrote: "Thought is action … your capacity to enact the concept as perceptuomotor activity" (pp. 161–163). Philosophically, Merleau-Ponty (1962) posited that people perceive the world first and foremost through their bodies, a type of inter-corporeality which he referred to as "enfleshment."

Although there are many theories of EC, all are united in their emphasis on the body and draw upon two common themes. First, the body and the world (environment) are integral to forming, integrating, and retrieving knowledge. To that end, knowledge is *grounded* or *situated* in the interactions between the individual and the environment. *Grounding* might occur when words or linguistic

[1]Steps adapted from the National Institutes of Health NCATS (2020) and Rubio et al. (2010).

[2]For example, in 2015 APA launched a new journal called Translational Issues in Psychological Science. In 2015, Kaslow identified "Translating Psychological Science for the Public" as one of her APA presidential initiatives, and appointed a task force to develop new strategies to communicate psychology to the public, with the idea that psychology can one day resemble the public's knowledge of—and demand for—medical information.

metaphors bind together individual, heterogenous instances underlying abstract concepts (Lakoff and Johnson, 1980; Mazzuca and Borghi, 2019)[3]. Second, knowledge is *simulated*: Thinking, or the *use* of knowledge, is re-experiencing the bodily states that were activated at the initial time of encoding, as experienced by a person's individualized interactions with the world (Barsalou, 1999; Barsalou, 2008; Gallese, 2009).

Recently, EC has expanded its reach into "4E cognition", which suggests people's cognitive activity is not only embodied, but also "extended, enacted, and embedded" in the perceptual and interactive richness of their environment (see Gallagher in Rowlands, 2010). Abrahamson et al. (2021) advanced Enactivism (Varela et al., 1991) as a philosophical framework that captures "thinking as situated doing" for classroom learning. The emphasis is placed on *students' experience* as their source knowledge rather than on the teacher transmitting content (Petitmengin, 2007). For example, a learner and their surrounding environment constitute a system, in which the learner's thoughts, actions, and metacognitive awareness/verbalizations (Flavell, 1979; Bernstein, 1996) may promote the discovery of new relations between their body and environment (Suwa, 2006).

## BOTH TEACHING AND LEARNING NEED TO BE RE-EXAMINED

Our current educational delivery systems (i.e., teacher education, pedagogy, curriculum) and approaches can be traced back to "disembodied" views of human thinking. Specifically, much of teaching pedagogy/curriculum continue to view learning as abstracted and separate from the body (Macrine, 2002) and fails to understand the latest psychological and neuroscientific evidence from EC. Similarly, teacher training/pedagogy, while emphasizing constructivist's approaches, tends to devolve-in-practice to positivist's skills in preparation for standardized tests (Klein et al., 2019). According to Nathan (2012), teaching continues to focus on foundational knowledge or "formalism first". Specifically, formalism first "incorrectly advocates the teaching/mastery of formalisms often considered prerequisite to applied knowledge" [that] "privileges formal, scientific knowledge over applied knowledge" (Nathan, 2012, p.126). Further, Nathan asserts that formalisms only gain their meaning with embodied experiences through real-world interaction and therefore the experiences are what ground formalisms, not the other way around. Similarly, Wertsch (1985) noted that a construct is shared when the action and affordances are experienced with the adult and contextualized in the real world.

### Rethinking Learning

Derived from EC principles, EL constitutes a contemporary pedagogical theory that emphasizes the use of the body in educational practice, as well as student-teacher interaction both in and outside the classroom (Smyrnaiou and Sotiriou, 2016; Kosmas and Zaphiris, 2018; Georgiou and Ioannou, 2019). EL posits that a person's own actions (and the observation of others' actions) interact with environmental affordances, and together scaffold the process of learning.

While EC uses similar approaches to active learning, EL includes a variety of body-based techniques (i.e., gestures, imitations, simulations, sketching, and analogical mapping) (Alibali and Nathan, 2007; Weisberg and Newcombe, 2017) that hold promise for understanding the role of action and experience in early development, as well as to scaffold learning in more formal educational settings (Kontra et al., 2012). Following suit, embodied design is a pedagogical framework that "seeks to promote grounded learning by creating situations in which students can be guided to negotiate tacit and cultural perspectives on phenomena under inquiry" (Abrahamson, 2013, p. 224).

## OUR MODEL: TRANSLATIONAL LEARNING SCIENCES RESEARCH FOR EMBODIED COGNITION AND EMBODIED LEARNING

In light of recent empirical demonstrations of how EC/EL works, our model of *Translation Learning Sciences Research* for Embodied Cognition and Embodied Learning has seven goals: 1) making sense of and disseminating clinical and empirical research findings; 2) closing the gap between research and application; 3) combining cognitive science and pedagogy to share pertinent information; 4) improving teaching and learning through embodied applications; 5) confirming or debunking current trends, (i.e., neuromyths); 6) elucidating conceptual frameworks for sensorimotor and body-based learning; and 7) recommending curriculum, designs, taxonomies, technology, and development to inform policy.

From these goals, we outline the following four action steps: 1) Promote the multidirectional and multidisciplinary integration of basic embodied research to elucidate or to debunk current trends in teaching and learning; 2) Compile the embodied research to be analyzed, translated, and make connections to improve pedagogical approaches, with the long-term aim of improving teaching and learning; 3) Develop and disseminate resources and tools to help individuals at all levels of expertise develop a better understanding of EL; 4) Focus on the creation of appropriate embodied curriculum and the development of taxonomies to identify objectives, and track outcomes that will assess whether program objectives and competency requirements are being met. We believe that our model can serve as an expeditious way to systematically collate, translate, and disseminate the latest embodied research geared towards improved learning outcomes. In other words, this is where science meets the real world of schooling.

In a larger research project, we have addressed steps 1 and 2 by carefully curating examples from leading experts to show how EC can be integrated into classroom practice (Macrine and Fugate, 2020). Such research examples are based on behavioral and neuroimaging experimentation in the fields of language and reading comprehension, STEM, and social-emotional knowledge. By way of a few noteworthy examples, Kiefer et al.

[3]Other theories suggest that there is no grounding necessary because there are no mental representations (Gallagher, 2005; Hutto, 2005; Thompson, 2007; Chemero, 2009; Hutto and Myin, 2012; Hutto and Myin, 2017).

(2015) found that young students who relied on physically writing (compared to typing) had improved word reading and word writing. James (2010) found that four-to-five year-old participants, who had practiced writing letters through handwriting (but not other ways), showed adult-like brain activation when subsequently viewing letters. Further, college students demonstrated better recall of handwritten notes vs. typed notes (Mangen et al., 2015). In addition, Glenberg and colleagues (Glenberg and Kaschak, 2002; Glenberg et al., 2008; Glenberg and Gallese, 2012) showed how vocabulary acquisition can be enhanced by shared communication and physical pantomime, both which allow for the grounding of information to concrete objects. In another example, Boaler and colleagues (Boaler et al., 2016) demonstrated how finger perception predicted learning math all the way through college, and that young children with good finger-based numerical representations showed better arithmetic skills. In addition, the panoply of motion-based technologies and interactive-user gaming platforms have allowed VR and AR designers to create technology-enabled EL experiences. Such technologies range from gesture-based to full-body interactive technologies, with the latter making up fewer options and focusing mainly on VR and AR technologies (Trninic and Abrahamson, 2012; Johnson-Glenberg, 2018; Georgiou and Ioannou, 2019).

Several of these researchers, and numerous others working within the field of learning design and practice, have turned such research findings into EL technologies for the classroom. As an example, the M*oved by Reading approach* uses simulation or "acting-out" in two stages to enhance reading (Glenberg et al., 2004). In the first stage, called *physical manipulation*, children manipulate toys to simulate the story that they are reading. The second stage is called *imagined manipulation*, where children are taught how to mentally simulate or imagine doing the actions. The authors found that physical and imagined manipulations contributed to larger gains in memory and comprehension than dis-embodied reading approaches. Gomez and Glenberg (2022) demonstrated the importance of pantomiming while reading new physics content. Abrahamson and colleagues designed multiple, successful embodied instruction design applications, called Mathematical Imagery Trainers (MITs). In one high technology-based project known as the *Kinemathics* project (Abrahamson et al., 2011), students move their arms in proportional distances to measurements of similar magnitude displayed on a screen. Using a trial-and-error approach, correct answers turn the screen green and incorrect ones turn it red, which reinforces the rules underlying the relationship (i.e., a 1:2 rule). And, in another specialized application, Abrahamson and Lindgren (2014) developed *MEteor,* an interactive MR simulation that uses a laser and floor-projected imagery. In this application, students use their bodies to simulate an orbit around a virtual planet to learn about formal concepts such as gravitational acceleration and mass.

Perhaps just as important is that many of these applications can be adapted to students with learning disabilities. Indeed, advances in EL have been utilized with students with ASD (De Jaegher, 2013; Eigsti, 2013; Eigsti, 2015), deaf students, and students with motor impairment (Kosmas et al., 2019; Tancredi et al., 2022).

In the remainder of this perspective, we focus on steps 3 and 4 of our model. Step 3 advocates for a coordinated effort - a type of interactive educational/cognitive-science consortium - among researchers, educational psychologists, teachers, school psychologists, policy makers, and textbook publishers to translate and disseminate/share the latest findings, applications, and implementation of the latest developments. These include bringing such issues to the attention of: 1) university-affiliated design-based research laboratories; 2) school personnel–primarily teachers but also technology experts and principals; 3) parents—as individuals and *via* various organized bodies–invested in school policy on infrastructure, resources, and pedagogy; 4) non-profit education-promoting groups, who are hampered neither by publication nor sales constraints; 5) commercial educational-technology companies with forward-thinking strategies; and 6) reporters, bloggers, etc. who cover the educational beat and can bring these issues to the attention of the wider public, including city, state, and federal policymakers. These many—and in rare occasions collaborations among them—could hasten the experimental application of cutting-edge research in the form of convivial instructional resources. For example, a national database of open-science materials and data could be coordinated to allow any teacher to use the materials and to contribute to "open science", which has become popular already in psychology[4].

To begin to address step 4, we have extracted the following key appropriate embodied principles (**Table 1**) for future practitioners, researchers, and teachers to guide the research-to-practice transition.

The final step will be for educators and policy makers to use these principles to develop taxonomies of embodied curriculum, identify learning objectives and outcomes, and track outcomes to assess whether program objectives and competency requirements are met. Specifically, "*in situ*" assessments will be needed, as retrospective measures of learning (e.g., written tests, etc.) are at odds with the very nature of EL (Georgiou and Ioannou, 2019). As Roschelle et al. (2011) point out: "Meaningful educational change almost always involves coordinating and aligning related changes (e.g., in curriculum, technology use, pedagogy, assessment, and school leadership)" (p. 33).

## SUMMARY AND FUTURE DIRECTIONS

Our *Translational Learning Sciences Research* for Embodied Cognition and Embodied Learning came about because there is a need for an expeditious pipeline to get the latest cognitive science and empirically validated educational applications out to the public. Our model provides a bi-directional conduit in which research findings and applications can flow quickly. We are advancing our model as a vehicle to continue to collate vetted examples of EL as they relate to EC theory. Our model is aimed at informing EL in an earnest way through a translational science approach[5]. We hope that it encourages

[4]see https://www.apa.org/science/about/psa/2019/02/open-science.

[5]Such a "translation" of psychology research to classroom-practice has, however, been done for research on metacognition (Flavell, 1979) (e.g. Tanner, 2012; Beach et al., 2020). Beach and colleagues have an entire manual on the role of metacognition in teaching and learning, highlighting four key findings that are similar in effect to our extracted teaching principles for embodied cognition.

**TABLE 1** | *Key Principles for Translational Learning Sciences Research for Embodied Cognition and Embodied Learning.*

| EC principle and generalized advice | Domain | Scientific findings* = classroom-vetted K-12 | Classroom resources/Links | Specific teaching principle |
|---|---|---|---|---|
| *1) The use of body-based learning (i.e., sensorimotor learning, including using whole-body and fingers, and gesturing).*<br><br>Teachers should promote body-based learning, including self-generated actions involving touch, sight, drawing, and writing. | Reading | Vocabulary acquisition, reading comprehension skills, and cued and spontaneous recall rely on connecting linguistic elements (e.g., the words and phrases in the linguistic input) to sensorimotor capacity (e.g., the perceptual or motor skills to which those linguistic elements refer) [Glenberg and Kaschak (2002), Glenberg et al. (2004)*, Kaschak et al. (2005), Pulvermuller (2005), Glenberg et al. (2007), Marley et al. (2007)*, Glenberg (2008), Glenberg et al. (2009)*, Glenberg et al. (2011)*, Zwaan (2014), Kaschak et al. (2017)*]. | *Embrace* and *Moved by Reading* programs https://www.movedbyreading.com/ | Teachers can encourage word learning and language comprehension through: 1) dialogic reading, in which the adult asks questions related to the text that are intended to prompt dialogue; 2) "acting out" vocabulary or sentences through play with a physical representation of content depicted in the text; and 3) performing iconic actions to illustrate word meaning through gesture or pantomime. |
| — | Reading | Taking notes with pen and paper (vs. typing) encourages summative understanding because of the slowness (but also richness) of physically writing [Mueller and Oppenheimer, (2014)]. | — | For language and material comprehension, teachers can encourage students to handwrite notes that are summative (and less dictated). Students' self-generated, summative arguments actions can be more powerful than memorization or writing notes verbatim. |
| — | Reading | Reading from print books (rather than digitally on computers or tablets) can enhance kinesthetic and tactile feedback and can improve information general comprehension. [Mangen (2008), Mangen et al. (2013)*, Delgado et al. (2018), Mangen et al. (2019)]. | — | Teachers can encourage paper books or electronic reading displays (e.g. Kindle), which more closely simulate the physicality of print books, especially for longer passages. |
| — | Handwriting | Exploring letters visual-haptically (vs. visual only) improves handwriting and is important for letter learning and early literacy [Naka (1998)*, Longcamp et al. (2003), Bara et al. (2004)*, Longcamp et al. (2005), Longcamp et al. (2008), Mangen and Velay (2010), Bara and Gentaz (2011)*, James and Engelhardt (2012), Kiefer et al. (2015)*, Mangen et al. (2015), Mangen and Balsvik (2016), James (2017)]. | — | Teachers can encourage learning to write by hand. |
| — | Math and Science | Finger use and perception predict mathematics achievement [Berteletti and Booth (2015), Boaler et al. (2016)]. | YouCubed Team: https://www.youcubed.org/wp-content/uploads/2017/03/Finger-Activities-vF.pdf | Teachers can encourage solving mathematical problems with real-world objects, rather than solving comparable symbolically presented problems. |
| — | Math and Science | Mathematical attainment is related to interceptive timing ability and is learned through perceptually guided actions that instantiate the concept as a movement form [Abrahamson (2004)*, Abrahamson (2007)*, Gracia-Bafalluy (2008)*, Reinholz et al. (2010)*, Abrahamson et al. (2011)*, Abrahamson (2014), Abrahamson et al. (2014)*, Abrahamson and Trninic (2015)*, Giles et al. (2018), Abrahamson et al. (2020)]. | 3D Multiplication Table (Embodied Design Laboratory): https://edrl.berkeley.edu/design/3d-multiplication-table/<br>Math Imagery Trainers (MITs) MIT-Proportion and MIT-Parabola (Embodied Design Laboratory) https://edrl.berkeley.edu/design/mathematics-imagery-trainer/<br><br>*Kinemathics* (Embodied Design Laboratory): https://edrl.berkeley.edu/projects/kinemathics/<br><br>Combinations Tower (Embodied Design Laboratory): https://edrl.berkeley.edu/design/combinations-tower/<br><br>YouCubed Team: https://www.youcubed.org/tasks/<br><br>4-Blocks NetLogo (Center for Connected Learning and Computer-Based Modeling) http://ccl.northwestern.edu/netlogo/docs/<br>Dice Stalagmite NetLogo (Center for Connected Learning and Computer-Based | Teachers can provide multi-dimensional experiences in mathematics, which include multiple opportunities to see and experience concepts through touch, sight, drawing, and writing in words. |

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**TABLE 1 |** (*Continued*) *Key Principles for Translational Learning Sciences Research for Embodied Cognition and Embodied Learning.*

| EC principle and generalized advice | Domain | Scientific findings* = classroom-vetted K-12 | Classroom resources/Links | Specific teaching principle |
|---|---|---|---|---|
| | | | Modeling): https://ccl.northwestern.edu/netlogo/models/DiceStalagmite | |
| — | Math and Science | Human capacity to perceive the environment in new ways is predicated on learning to move in new ways because perception of scientific concepts is inherently for action [Mechsner et al. (2001), Alibali and Nathan (2012)*, Walkington et al. (2019), Nathan et al. (2020)]. | Block Stalagmite (Embodied Design Laboratory): https://edrl.berkeley.edu/design/4-block-stalagmite/<br>The Eye Trick (Embodied Design Laboratory): https://edrl.berkeley.edu/design/the-eye-trick/<br><br>*MEteor: Developing Physics Concepts through Body-based Interaction with a Mixed Reality Simulation (Lindgren et al., 2016)*<br><br>The Hidden Village: Mathematical Reasoning through Movement https://multiplex.videohall.com/presentations/1662<br><br>Magna-AR: https://www.vieyrasoftware.net/physics-toolbox-ar<br><br>PhysicsToolbox: https://play.google.com/store/apps/details?id=com.chrystianvieyra.physicstoolboxsuite&hl=en_US<br><br>HistoBlocks: https://ccl.northwestern.edu/netlogo/models/HistoBlocks<br><br>The Marbles Scooper: https://edrl.berkeley.edu/design/the-marbles-scooper/<br><br>Data science K-12 initiative: https://www.youcubed.org/resource/data-literacy/<br><br>SMALLab Learning, LLC: https://www.smallablearning.com/research<br>Ratio and Proportion (Phet Interaction Simulations): https://phet.colorado.edu/en/simulation/ratio-and-proportion. | Teachers can create conditions that enact movement that captures the dynamical sense of a concept. |
| — | Math and Science | Gestures are spontaneous or purposeful movements of the body that often accompany speech, serve as a way to convey ideas, and predict the quality of one's argument in mathematics and sciences (e.g. physics) [Kontra et al. (2015), Johnson-Glenberg et al. (2016)*, Johnson-Glenberg and Megowan-Romanowicz (2017), Johnson-Glenberg (2018), Megowan-Romanowicz (2022)]. | — | Teachers can consider how gestures support understanding and reveal learners' struggles and understandings.<br><br>Teachers can directly interact with learners' gestures when describing their embodied experiences with embodied learning technologies by: (1) pointing out/highlighting aspects of the gesture; and/or (2) contributing new dynamic gestural imagery to the gesture.<br><br>Teachers can attend to not only what learners say, but also to learner's movements, idiosyncratic forms of perception, and how learners interpret their embodied experiences. Noticing these behaviors can help teachers prompt perceptual-motor activity at timely moments. |
| *2) Imitative body-based learning from others, including attention to other's body movements.*<br><br>Teachers need to be attentive to students' whole-body learning | Socio-Emotional | Observational learning is important for acquiring and communicating knowledge. The mirror neuron system (MNS) responds robustly to observation and imitation of face and hand actions [Iacoboni et al. (2005), Immordino-Yang and Damasio (2007), Caspers et al. (2010), Caramazza et al. (2014), Aziz-Zadeh et al. (2018), Ferrari and Coudé | | Teachers can engage in demonstrating a skill, and students should engage in subsequent imitation or emulation to enhance observational learning. |

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**TABLE 1 |** (*Continued*) *Key Principles for Translational Learning Sciences Research for Embodied Cognition and Embodied Learning.*

| EC principle and generalized advice | Domain | Scientific findings* = classroom-vetted K-12 | Classroom resources/Links | Specific teaching principle |
|---|---|---|---|---|
| experiences and intentionally incorporate movement into learning activities, which can increase the connection between the physical environment and academic goals through situated learning. Teachers should assess students' developing understanding by attending to both their gestures and body language. | | (2018), Keysers et al. (2018), Butera and Aziz-Zadeh (2022)]. | | |
| — | All | Students learn through repeatedly attempting to reconstruct actions performed by others, and follow action goals of others [Flanagan and Johansson (2003), Gerofsky, (2011)*, Hall and Nemirovsky (2012), Gredebäck and Falck-Ytter (2015), Vogelstein et al. (2019)]. | — | Teachers can use goal-directed human movement to illustrate new concepts.<br><br>Teachers can use simple bodily movements to help learners understand more advanced concepts (e.g., opposing forces as argument opposition) as they develop. |
| *3) Responsive Teaching*<br><br>Teachers should support student engagement by monitoring what the individual is doing, encouraging them to come up with their own strategies and reflect. | Socio-Emotional | Teacher and students who engage in joint attention experience more positive affect, likely attributable to increased agency [Steinbrenner and Watson (2015), Grynszpan et al. (2017)]. | — | Teachers can engage in joint attention with the student by encouraging collaborative situated interactions. |
| — | All | Intercorporeal attunement (i.e., responsiveness) is bidirectional, that is, students attune to teachers. In conversations, even multi-person discussions, speakers are constantly returning to each other. This is a rapid, iterative, and reciprocal process [Radford and Roth (2011), Shvarts and Abrahamson (2019)]. | — | Teachers can create a classroom climate that encourages students to express and discuss how concepts "look," "move," "feel," etc.<br><br>Teachers can make instructional decisions based on what they can *see* that was not understood. |
| — | All | Responsive teaching involves: 1) drawing out, attending to, and engaging with aspects of learners' ideas that have potential disciplinary value or substance; and 2) engaging in ongoing *proximal formative assessment* (e.g., continuously monitoring students' ideas to adapt instructional support in the moment) [Robertson et al. (2016), Flood et al. (2020), Flood et al. (2022)]. | — | Teachers can try to reformulate learners' ideas to help them extend and connect these ideas with new disciplinary understandings. One way to achieve this is through the practice of *revoicing*, (i.e., recasting learners' multimodal contributions by repeating some content) yet also reformulating (modifying the content of) and/or elaborating (adding new content to) the ideas learners have shared. |
| — | Special Needs | Individuals with motor and sensory impairment will have different experiences over time that shape how they come to understand the world, mandating the need for including "inclusive design" [Ma (2017), Abrahamson et al. (2019), Chen et al. (2020), Tancredi et al. (2022)]. | Balance Board Math (Embodied Design Laboratory/Tancredi: https://edrl.berkeley.edu/projects/balance-board-math/<br><br>Magical Musical Mat (Embodied Design Laboratory/Chen): https://edrl.berkeley.edu/projects/magical-musical-mat/<br><br>SignEd\|Math (Embodied Design Laboratory/Krause): https://edrl.berkeley.edu/projects/signedmath/ | |
| *4) Use of manipulatives with relevant affordances (including AR/VR but also "simpler" actions)* | All | Augmented reality (AR) technologies enhance and expand opportunities to learn through moving and can improve both visuospatial capabilities and enhanced student-reported interest leading to more | Titans of Space (Drash VR LLC): http://www.drashvr.com/titansofspace.html | Teachers can encourage the use of concrete manipulatives (e.g., blocks, chips, Dienes blocks, Geotiles, balance scales, paper clips, popsicle |

(Continued on following page)

**TABLE 1 |** (*Continued*) *Key Principles for Translational Learning Sciences Research for Embodied Cognition and Embodied Learning.*

| EC principle and generalized advice | Domain | Scientific findings* = classroom-vetted K-12 | Classroom resources/Links | Specific teaching principle |
|---|---|---|---|---|
| Teachers should root themselves in practices that exemplify interaction that supports conceptual modeling, including digital simulations as well as physical manipulatives, especially for STEM fields. | | accurate performance (vs. traditional instruction) [Carbonneau et al. (2013), Lindgren and Johnson-Glenberg (2013), Abrahamson and Lindgren, (2014), Donovan et al. (2014), Carbonneau and Marley (2015), Johnson-Glenberg et al. (2016)*, Lindgren et al. (2016)*, Johnson-Glenberg and Megowan-Romanowicz (2017), Vieyra et al. (2020), Donovan and Alibali (2021), Donovan and Alibali (2022), Megowan-Romanowicz (2022); Vierya and Vierya (2022)*]. | Catch a Mimic (Embodied-Games.com): www.embodied-games.com | sticks, and beanbags) and computerized or AR technologies created and vetted for learning. |
| — | All | All technologies have their own material affordances and sensorimotor contingencies, which frame and constrain a person's interaction with a device [Gibson (1979), Gaver (1991), Kamii et al. (2001), Moyer (2001)]. | — | Teachers can consider the following when deciding whether and how to use a given manipulative: 1) identifying the target concept, considering how the object under consideration relates to the target concept; 2) considering what actions the object affords; and 3) considering how those actions relate to the target concept. |
| — | All | Manipulatives are most effective when their design enables students forms of sensorimotor *engagement* that prompt diverse ways of reasoning related to the content, as well as *coordinating* among these different ways of reasoning [Abrahamson et al. (2014)]. | — | — |
| *5) Bodily-based sensory awareness of internal states*<br><br>Teachers should encourage students to express pride, enjoyment, and hopes about their learning, and engage in positive attitudes about the efficacy of body-based learning. | Socio-Emotional | Body-based approaches and therapies which lead to the disambiguation of affective states can improve emotion regulation and perception of emotion, as well as improve attention and performance in the classroom [O'Conner et al. (2017), Jagers et al. (2019)]. | CASEL: https://casel.org/resources/ | Teachers can capitalize on teaching emotion vocabulary and mindfulness to individuals to not only improve emotional interactions and regulation, but also to improve attention, focus, and cognitive awareness, which all facilitate academic performance. |
| — | Socio-Emotional | Individuals higher in granularity report more flexible emotional regulation abilities [Barrett et al. (2001), Boden et al. (2012)], have a less reactive coping style [Tugade et al. (2004)], and are less biased by incidental emotions when making moral decisions [Cameron et al. (2013), Fugate and Wilson-Mendenhall (2022)]. | — | Teachers can label student's emotional states and include socio-emotional learning (SEL) into the classroom. Emotions can be labeled and incorporated into the category knowledge about human behavior. |
| — | Socio-Emotional | Knowing one's own feelings may also help with understanding others' feelings [Saarni (1997)]. | — | — |
| — | Socio-Emotional | The awareness practices that characterize mindfulness-based interventions are thought to improve emotion regulation by cultivating a more fine-grained awareness of what is occurring in one's mind [Hill and Updegraff (2012), Roemer et al. (2015), Carsley et al. (2018)]. | — | Teachers can consider adding in mindfulness practices into the classroom. |

cognitive science and educational researchers to offer and make their research available across the fields of educational psychology, educational policy, and teacher education to improve student outcomes and classroom pedagogy. We want to improve communication between scientists and practitioners and to avoid the occurrence of misconceptions, such as neuromyths to shape their pedagogies (Tan and Amiel, 2019). Our model was developed to reimagine how educators can access reliable research to inform their own pedagogy to create a more equitable and just schooling for all.

While we applied this new education-based translational research model to embodied cognition for teaching and learning, we believe that our model can also be used in different educational research contexts. Thus, this approach could provide a vehicle for the dissemination of theory-driven empirical findings translated into evidence-based classroom practice and enable bi-directional suggestions for future research, best practice, and theory development. Ultimately, the continued development of such pathways will lead to the advancement of—and efficient translation of—the latest cognitive science and educational psychology research findings for the educational community.

## AUTHOR CONTRIBUTIONS

SM and JF contributed to all aspects of the article including model development and writing, as well as approved the submitted version.

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# Impacts of Color Coding on Programming Learning in Multimedia Learning: Moving Toward a Multimodal Methodology

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In the present study, we tested the effectiveness of color coding on the programming learning of students who were learning from video lectures. Effectiveness was measured using multimodal physiological measures, combining eye tracking and electroencephalography (EEG). Using a between-subjects design, 42 university students were randomly assigned to two video lecture conditions (color-coded vs. grayscale). The participants' eye tracking and EEG signals were recorded while watching the assigned video, and their learning performance was subsequently assessed. The results showed that the color-coded design was more beneficial than the grayscale design, as indicated by smaller pupil diameter, shorter fixation duration, higher EEG theta and alpha band power, lower EEG cognitive load, and better learning performance. The present findings have practical implications for designing slide-based programming learning video lectures; slides should highlight the format of the program code using color coding.

**Keywords: color coding, EEG, eye-tracking, programming learning, multimedia learning**

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## INTRODUCTION

Each object has its own color, be it a color such as red, green, or blue, or be it colorless (i.e., white, black, or gray). A considerable amount of scientific research on color psychology has been conducted on all aspects of color. The theoretical basis of color and psychological functioning is based on the physiological model proposed by Goldstein (1942). Goldstein discussed that color naturally causes physiological reactions that manifest in emotional experience, cognitive focus, and motor behavior.

Color carries a psychologically relevant meaning, and the colors seen influence psychological functioning (Elliot and Maier, 2012). The first study on this issue (Schauss, 1979) suggested that pink reduced physical strength and aggression. Black (Frank and Gilovich, 1988) is associated with evil, death, and other negative concepts. Red is related to happiness and facilitates non-systematic cognitive processing (Soldat et al., 1997). Therefore, color can be regarded as a type of non-content visual stimulus.

According to perceptual theory, stimuli with distinguishing features, such as color, are conducive to visual search (Treisman and Gelade, 1980; Itti and Koch, 2000). Color coding impacts learners' cognitive processing as material-oriented interventions in multimedia learning. The salience of color can attract learners' attention and guide it toward the relevant visual information that designers want learners to process (Hillstrom and Chai, 2006; Jamet et al., 2008). From the perspective of perceptual theory, this is a bottom-up processing method that affects the learning process and learning effect through the visual design of multimedia.

In his Cambridge Handbook of Multimedia Learning, Mayer classifies color as visual signaling (Mayer, 2005a). The signaling principle, also known as the cueing principle, points out that people learn more deeply from multimedia materials when signals are added to guide their attention to the relevant elements of the material or highlight the organization of the material (Mayer, 2005a; de Koning et al., 2009).

When color coding is added to highlight the organization of learning materials, learners can obtain more information from multimedia messages. In the process of multimedia learning, learners must integrate the information conveyed through external representations into coherent mental representations. However, there is evidence that learners often need instructional support to identify correspondence and establish relationships between them (e.g., Seufert, 2003; Seufert and Brünken, 2006). Color coding is the non-lexical information added to learning materials that can attract learners' attention and promote the selection, organization, and integration of instructional elements (de Koning et al., 2009). Many studies have shown that color coding in multimedia materials facilitates learning (Jeung et al., 1997; Kalyuga et al., 1999; de Koning et al., 2007; Ozcelik et al., 2009; Jamet, 2014; Richter et al., 2016).

Many researchers have explained from the perspective of cognitive load theory that color cues can reduce learners' overall cognitive load and avoid overload, resulting in improved academic performance (Sweller, 1988; Paas et al., 2003).

Subjective measures are the most common methods used to assess cognitive processing (Mutlu-Bayraktar et al., 2019). Subjective self-reports on personal feelings can provide valuable information, but validity and corroboration problems arise (Bethel et al., 2007). Participants may not answer exactly how they feel, but in the way they believe others will answer. Furthermore, color is an implicit affective cue that seems to influence psychological functioning without people's awareness (Friedman and Förster, 2010). Thus, physiological signals help to better understand the potential responses of participants during observations.

Eye tracking data can offer valuable information about learners' cognitive processes. As a cognitive processing assessment method, it helps reveal information about the underlying cognitive processes during multimedia learning (Just and Carpenter, 1976; Antonenko et al., 2010; van Gog and Scheiter, 2010). Many studies have incorporated eye tracking measures to investigate perceptual processes as indicators of cognitive activity (e.g., Hyönä, 2010; Jarodzka et al., 2010; Park et al., 2015a,b). For instance, pupil diameter has been shown to be a sensitive measure of mental demands. Usually, the pupil dilates to meet increased task processing demands (van der Wel and van Steenbergen, 2018; Scharinger et al., 2020). Furthermore, fixation duration is related to the continuous psychological processes associated with present information (Just and Carpenter, 1976). Total fixation time is considered to be a sign of total cognitive processing engaged with fixation information (Just and Carpenter, 1980; Rayner, 1998). Therefore, fixation duration is a very useful measure of cognitive load (Holmqvist et al., 2017).

Electroencephalography (EEG) can non-invasively assess brain activity in an authentic environment. It measures the electrical activity generated by the brain through electrodes placed on the scalp. Changes in the power of neural oscillations measured with EEG are also a credible method for examining cognitive processes in multimedia learning (Antonenko and Niederhauser, 2010). EEG signals are voltage signals generated by neural activities, and these neural activities change with cognitive processes such as learning (Lin and Kao, 2018). Moreover, EEG power reflects the capacity or performance of cortical information processing. Many prior studies have used EEG to detect, estimate, or predict human brain activities (Gevins and Smith, 2003; Galán and Beal, 2012; Yoshida et al., 2014). These measurements vary with different levels of cognitive stimulation (Berka et al., 2004), which makes it a credible choice for measuring and continuously assessing cognitive load in a learning environment (Klimesch, 1999; Anderson and Bratman, 2008).

The alpha and theta changes in rhythms reflect what is happening in a subject's information processing, even if the subject is not aware of such changes or cannot express them in words (Basar, 1999; Klimesch et al., 2005). A number of researchers have shown that alpha and theta activities are the most relevant measure of task difficulty or cognitive load amidst various task demands (Penfield and Jasper, 1954; Gale and Christie, 1987; Sterman et al., 1994; Gevins et al., 1997). Beta waves have also been demonstrated to be related to perception and cognition (Singer, 1993; Haenschel et al., 2000; Wrobel, 2000). Increased beta waves have been correlated with anxious thinking.

Electroencephalography signals are non-stationary, dynamic, and non-linear time series. Many researchers have used non-linear parametric measures to quantify EEG data (Gribkov and Gribkova, 2000). The degree of chaos in time series data can be measured using wavelet entropy (Rosso et al., 2001), sample entropy, and approximate entropy (Richman and Randall, 2000). Entropy is an accurate measure of complexity (Pincus, 1995; Chen et al., 2009), i.e., higher entropy refers to higher complexity (Parbat and Chakraborty, 2021).

Color acts as a non-conscious prime that affects psychological function in subtle ways (Bargh, 1990). Meanwhile, EEG has a high temporal resolution and has been proven to accurately reflect subtle changes that can be distinguished and quantified in a second-by-second time frame. Therefore, EEG can provide an index of the utilization of resources for the color coding effect on learners.

In the present study, we sought to determine the color coding effect on programming learning in multimedia learning. Based on the above analysis, we hypothesized that color coding is beneficial for learning. We recorded eye tracking and EEG data simultaneously to provide further insights on assessing cognitive processing. These recordings stemmed from both the central (i.e., brain) and autonomic (i.e., pupillary response) nervous systems. We focused on measuring the EEG theta, alpha, and beta frequency band power; pupil dilation; and fixation

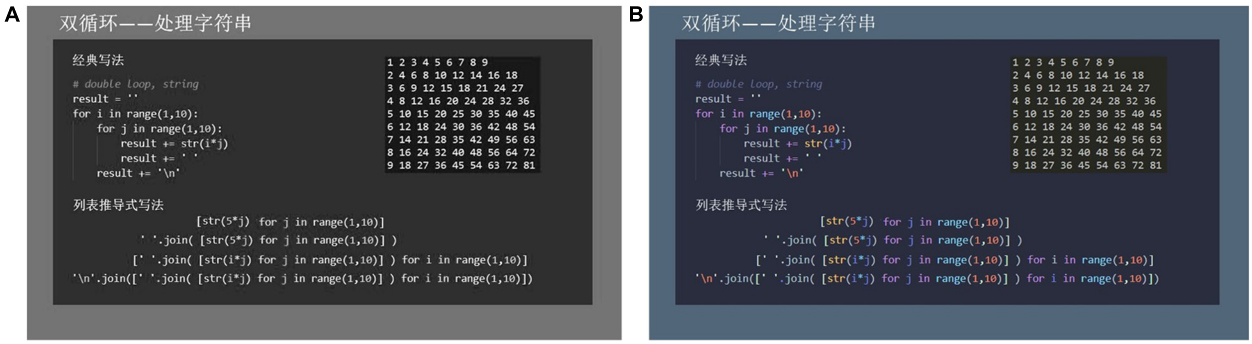


**FIGURE 1 |** Two slide-based video lectures in **(A)** grayscale design and **(B)** color-coded design.

duration – all of which are specific indications of cognitive processing needs.

# METHOD

## Participants

The participants comprised 42 graduate students recruited from the Zhejiang University of Science and Technology in China. There were 26 male and 16 female participants, all of whom were over 18 years old ($M$ = 20.81, SD = 1.13).

The participants were selected from those who did not take the "Object-oriented Python Programming" course in order to ensure that the participants did not have any prior knowledge of the learning material. However, all participants had taken C/C++ courses to ensure that they had the necessary programming foundation. In addition, their C/C++ course scores (with a maximum possible score of 100) were used to ensure that the participants had similar prior knowledge of the learning material.

All participants had normal or corrected-to-normal vision and hearing. They signed an informed consent form before the experiment and received a small gift at the end of the study to thank them for their time and effort.

## Materials

Two different versions of video lectures were used in the present study, which differed only with regard to the color of the presented text. All other features were maintained at constant values.

The learning materials are shown in **Figure 1**. Each video lecture included the same PowerPoint presentation, accompanied by a lecture given by a professor who is proficient in teaching the topic. As illustrated in **Figure 1A**, the grayscale design was achromatic. **Figure 1B** shows the color-coded design which used the "Palenight Theme" to highlight code format, which is widely utilized in programming. The video lectures were identical in speed, sound, and light. The materials were not self-paced and did not allow learners to start, stop, or replay short sequences. Each video lecture lasted approximately 5 min and introduced the topic of "List Expression in Python" in Chinese.

## Eye Tracking and Electroencephalography Recording

A Tobii T120 Eye Tracker device was used to collect data regarding the participants' eye movements. The data rate of Tobii T120 for tracking was 120 Hz. Participants completed a 9-point calibration and validation procedure before watching the video lecture. They sat in front of a 17-inch monitor to view the lectures at a distance of 60 cm.

Electroencephalography was recorded at 15 electrode sites (Fp1, Fp2, F7, F3, Fz, F4, F8, T7, Cz, T8, P7, Pz, P8, O1, O2), which were positioned according to the international 10–20 system (Jasper, 1958). CPz served as a reference during recording. Data were referenced to the average of all electrodes and the ground electrode was located at the AFz. The conductive gel was inserted into each electrode with a blunt needle syringe to reduce the impedance to <5 kΩ.

## Measurements

### Perceptions of Task Difficulty

The participants completed a nine-point Likert-type (1 = strongly easy, 9 = strongly difficult) survey on their perceptions of task difficulty, which asked the question, "How easy or difficult was the material to understand?" (Kalyuga et al., 2000). This item has been proven to be a reliable questionnaire for measuring the extraneous cognitive load experienced by learners in the learning process (Tuovinen and Paas, 2004; Kalyuga and Sweller, 2005).

### Individual Interest in Programming Learning

To avoid the influence of individual interest on the experimental results, the direct measurement method was used to measure the subjects' interest in program learning. All participants were also given a nine-point Likert-type (1 = strongly uninterested, 9 = strongly interested) measure of their individual interest in programming learning, which asked, "How much you did like computer programming learning?"

### Learning Performance Test

A learning performance test was developed to measure the acquisition of knowledge presented in the video lecture. It measured the learners' understanding of key concepts in the learning materials and their ability to apply the concepts to solve

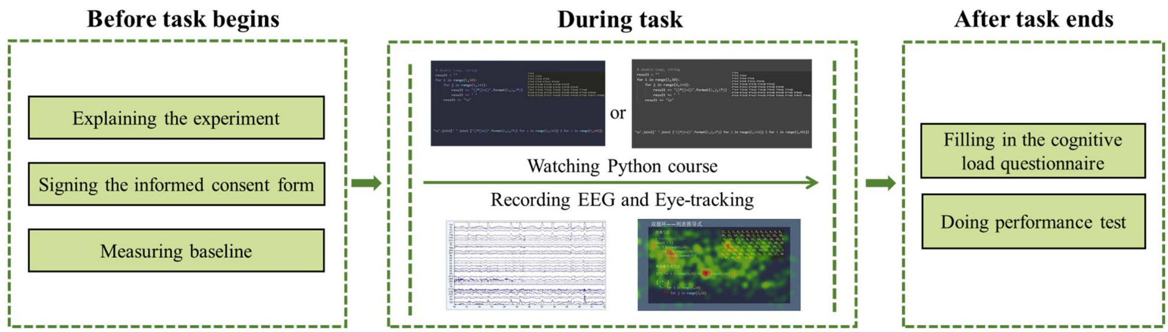


**FIGURE 2 |** Experimental procedure. The experiment used a between-subjects design.

problems. The test consisted of ten items and the participants received one point for each correct answer. The total possible learning performance score was 10.

## Procedure

As illustrated in **Figure 2**, the participants were randomly assigned to one of the two following video lecture conditions: the grayscale design condition ($n$ = 21) and the color-coded design condition ($n$ = 21). The procedure was conducted through computer programs and paper-and-pencil questionnaires. Each subject was individually tested in a laboratory setting for approximately 40 min. Prior to the task, each participant learned about the experimental procedure and signed an informed consent form. The participants then closed their eyes for 3 min so we could take a baseline measurement. Thereafter, the participants viewed one of the video lectures. Participants' EEGs and eye tracking data were recorded synchronously during the entire experiment. Finally, the participants completed the cognitive load questionnaire and learning performance test immediately after viewing the assigned lecture.

## Data Preprocessing and Analysis

The EEG data analysis was performed using MATLAB. Four data points were deleted for low-signal quality. Therefore, the color-coded design group included 19 data points and the grayscale design group included 19 data points.

First, the DC components were removed at 1 Hz using a finite impulse response (FIR) high-pass filter. Then, the other artifact noises at high frequencies were removed using an FIR low-pass filter at 50 Hz. Subsequently, the EEG data were referenced by subtracting the average of all collected electrodes from each individual electrode. An independent component analysis was also conducted to remove electrooculography (EOG) and eye artifacts (Jung et al., 2000; Delorme et al., 2007). Finally, the Hilbert–Huang transform (HHT) technique was used to calculate the power spectrum of each EEG epoch (4 s) with a frequency resolution of 0.1 Hz (Huang et al., 1998).

In the present study, we applied both the linear method (i.e., average power) and non-linear method (i.e., spectral entropy) on EEG data to evaluate the participants' cognitive processing.

The power of five standard EEG rhythms, i.e., delta (0.5–4 Hz), theta (5–8 Hz), alpha (9–12 Hz), beta (13–32 Hz), and gamma (33–50 Hz), were computed by averaging the spectral powers in the corresponding frequency bands (Sghirripa et al., 2020; Pi et al., 2021). We slid the EEG data recorded in the experiment with a window size of 4 s to calculate the power of the five frequency bands corresponding to each window. By this means, we obtained the relative power changes of each participant in the five frequency bands during the learning process as well as the average power of all participants. For the same sliding windows, we calculated the approximate entropy value to present the pattern repeatability of the EEG time series. A larger entropy indicates less predictability.

Meanwhile, we calculated the average pupil dilation data for each trial stimulus. To synchronize with EEG features, we calculated the average of the eye tracking features in the corresponding window size (i.e., 4 s).

# RESULTS

One-way analysis of variance (ANOVA) and Mann-Whitney $U$ tests were used to make comparisons across the two groups. One-way ANOVA was used on the dependent variables that met the normality assumption to conduct an ANOVA. The Mann-Whitney $U$ test was used as a non-parametric test of equivalence on dependent variables whose skewness and kurtosis values indicated that they did not meet the assumption of normality (Fritz et al., 2012; Legesse et al., 2020). The Mann-Whitney $U$ test is most sensitive to changes in the medium.

Effect sizes were measured by $\eta_p^2$ for the one-way ANOVA, with $\eta_p^2$ = 0.01 considered a small effect, 0.06 a medium effect, and 0.14 a large effect (Cohen, 1988).

Effect size were estimated by Mann-Whitney $U$ tests, the $z$ value can be used to calculate an effect size, such as the r proposed by Cohen (1988). Cohen's guidelines for r are that a large effect is 0.5, a medium effect is 0.3, and a small effect is 0.1 (Coolican, 2009).

## Control Variables

The first step in the analysis was to determine whether there were differences in prior knowledge and individual interest between the two groups. The descriptive statistics of control variables under the two conditions are presented in **Table 1**. **Figure 3A** showed boxplot of subjective ratings of individual interest in the two conditions. For each variable (i.e., prior knowledge and individual interest), a one-way ANOVA was conducted with the group as the between-subjects factor. The results revealed no main effect for either control variable. For prior knowledge, $F(1,38) = 0.18$, $p = 0.67$; for individual interest, $F(1,38) = 0.11$, $p = 0.75$. The results indicate that there was no difference between the two learning conditions in terms of prior knowledge and individual interest.

## Learning Performance

As illustrated in **Table 2**, the participants who studied the color-coded video lecture had higher scores on the performance test than those who studied the grayscale video lecture. A one-way ANOVA revealed that the learning performance across the two groups was statistically significant, with $F(1,38) = 5.65$, $p = 0.028$, $\eta_p^2 = 0.23$, indicating that the color-coded group performed better than the grayscale group in the post-test. The effect of the material format on learning performance was found to be significant with a large effect size. This result supports our hypothesis.

## Subjective Ratings of Perceived Task Difficulty

**Figure 3B** showed boxplot of subjective ratings of perceived task difficulty in the two conditions. The one-way ANOVA of task difficulty scores revealed a main effect for color-coded design, with $F(1,38) = 7.83$, $p = 0.009$, $\eta_p^2 = 0.19$. As illustrated in **Table 2**, learners who viewed grayscale video lectures rated the difficulty of the learning material to be higher than those who received color-coded video lectures. The results revealed that the color-coded design reduced the perceived difficulty of the learning task.

**TABLE 1 |** Means and standard deviations for control variables.

| | Color-coded group (*N* = 19) | | Gray-scaled group (*N* = 19) | |
|---|---|---|---|---|
| **Dependent variable** | ***M*** | ***SD*** | ***M*** | ***SD*** |
| Prior knowledge | 80.20 | 2.82 | 80.10 | 2.14 |
| Individual interest | 4.95 | 2.04 | 4.74 | 2.08 |

## Physiological Measures of Cognitive Processing

### Eye-Tracking Data Analysis

The descriptive statistics of all eye-tracking variables in the two conditions are presented in **Table 3**. A one-way ANOVA showed that there was a significant main effect of color coding design ($F(1,37) = 8.28$, $p = 0.008$, $\eta_p^2 = 0.24$; $F(1,37) = 5.19$, $p = 0.031$, $\eta_p^2 = 0.13$) on left and right pupil diameters. The subjects who were given the color-coded material had a smaller left pupil diameter than those who were given the grayscale material. Accordingly, the right pupil diameter was significantly larger in the grayscale condition than in the color-coded condition.

One-way ANOVA also revealed a significant difference in gaze event duration on color-coded design across experimental conditions, with $F(1,37) = 4.35$, $p = 0.047$, $\eta_p^2 = 0.143$. Participants who viewed video lectures with grayscale design had longer fixation durations than those who viewed video lectures with color-coded design.

### Electroencephalography Data Analysis

#### *Electroencephalography Power*

The descriptive statistics of all variables of EEG power under the two conditions are presented in **Table 4**.

One-way ANOVA was conducted with the between-subjects factors of the color-coded design condition and delta power, theta power, alpha power, beta power, and gamma power as the dependent variables. The results are shown in **Table 4**.

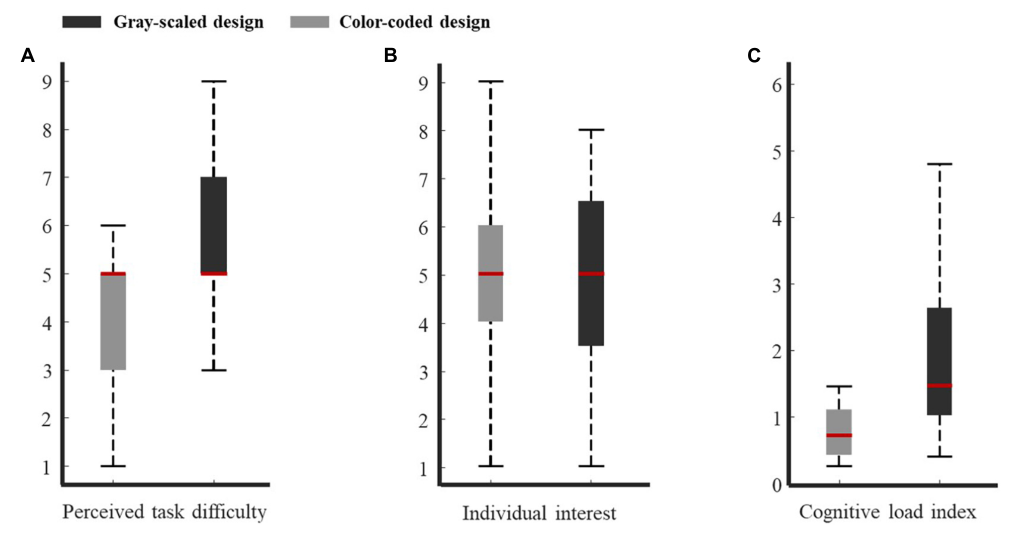


**FIGURE 3 |** Boxplot data for participants in two conditions. **(A)** Perceived task difficulty. **(B)** Individual interest. **(C)** Cognitive load.

The one-way ANOVA revealed significant main effects of color coding ($F(1,37) = 9.36$, $p = 0.004$, $\eta_p^2 = 0.206$; $F(1,37) = 4.43$, $p = 0.042$, $\eta_p^2 = 0.110$; $F(1,37) = 4.89$, $p = 0.034$, $\eta_p^2 = 0.119$; $F(1,37) = 4.40$, $p = 0.043$, $\eta_p^2 = 0.109$) on theta, alpha, beta and gamma power. However, there was no difference in delta power between the two learning conditions.

As shown in **Table 4**, the participants had higher theta and alpha power when they were shown a color-coded video lecture, and in turn had higher beta power when they were shown a grayscale video lecture.

Since the connection between EEG power and cognitive processes is more obvious in some regions than others, we further calculated the main effect of different electrodes on delta power, theta power, alpha power, beta power, and gamma power in both conditions. The results are shown in **Figures 4–8**.

There was no difference in the 15 electrodes on delta power across the two learning conditions (**Figure 4**). The participants had significantly higher theta power when learning through color-coded video lectures than through grayscale ones in all electrode regions (see **Figure 5**). In the Fp1, Fp2, F3, T8, Cz, P8, O1, and O2 regions, the participants had significantly higher alpha power when learning through color-coded video lectures than through grayscale ones (see **Figure 6**). There was a significant difference in beta power in the Fp1, F3, F7, F8, Fz, F4, T8, and Cz regions across the two learning conditions (see **Figure 7**). For gamma power, the Fp1, Fp2, Fz, and F4 regions showed significant differences (see **Figure 8**).

We chose the regions that had significant differences and adopted $\beta/(\theta + \alpha)$ to evaluate the cognitive load. $\beta/(\theta + \alpha)$ has proven to be very effective in quantifying the state of mental workload (Berka et al., 2007). The subjects who received the grayscale learning material had a higher cognitive load ($M = 2.05$, SD = 1.56) than those who received the color-coded learning material ($M = 0.96$, SD = 0.87). **Figure 3C** showed boxplot of cognitive load in the two conditions. The Mann-Whitney $U$ test likewise revealed a significant difference across the two study conditions in cognitive load ($U = 85$, $p = 0.005$, $r = 0.45$). The effect of the material format on cognitive load was found to be significant, with a large effect size. This outcome indicates that the participants who viewed grayscale video lectures required more mental processing.

### *Spectral Entropy*

The descriptive statistics of all variables of spectral entropy under the two conditions are presented in **Table 5**.

One-way ANOVA revealed statistically significant differences across the experimental conditions on approximate entropy ($F(1,37) = 624.03$, $p < 0.001$, $\eta_p^2 = 0.617$), sample entropy ($F(1,37) = 191.58$, $p < 0.001$, $\eta_p^2 = 0.331$), and wavelet entropy ($F(1,37) = 27.31$, $p < 0.001$, $\eta_p^2 = 0.069$). The results indicated that learners who received the grayscale learning material had higher spectral entropy than those who received the color-coded learning material. The results suggest that compared to participants who watched color-coded video lectures, the participants who watched grayscale video lectures had a heavier mental load.

**TABLE 2 |** Means and standard deviations of learning performance and perceived task difficulty.

| | Color-coded group (*N* = 19) | | Gray-scaled group (*N* = 19) | |
|---|---|---|---|---|
| **Dependent variable** | ***M*** | ***SD*** | ***M*** | ***SD*** |
| Learning performance | 5.09 | 2.07 | 3.10 | 1.73 |
| Perceived task difficulty | 4.28 | 1.23 | 5.71 | 1.76 |

**TABLE 3 |** Means and standard deviations of eye-tracking variables.

| | Color-coded group (*N* = 19) | | Gray-scaled group (*N* = 19) | |
|---|---|---|---|---|
| **Dependent variable** | ***M*** | ***SD*** | ***M*** | ***SD*** |
| Pupil diameter left | 3.29 | 0.35 | 3.71 | 0.42 |
| Pupil diameter right | 3.37 | 0.31 | 3.72 | 0.46 |
| Fixation duration | 218.12 | 103.23 | 314.00 | 137.50 |

**TABLE 4 |** Means and standard deviations of EEG power variables.

| | Color-coded group (*N* = 19) | | Gray-scaled group (*N* = 19) | |
|---|---|---|---|---|
| **Dependent variable** | ***M*** | ***SD*** | ***M*** | ***SD*** |
| Delta | 38.00 | 15.85 | 35.26 | 18.9 |
| Theta | 16.12 | 5.83 | 10.70 | 5.08 |
| Alpha | 16.37 | 8.60 | 11.72 | 4.36 |
| Beta | 26.46 | 13.02 | 38.11 | 18.92 |
| Gamma | 3.11 | 1.90 | 4.58 | 2.39 |

## DISCUSSION

The main purpose of the present study was to investigate the impact of color coding on programming learning in multimedia learning by measuring learning performance and cognitive processing using a combination of eye tracking and EEG data. The results indicated that the participants who studied the learning material with the color-coded design had higher learning performance than those who studied the learning material with the grayscale design. Our findings are in line with those of a previous study on the color coding effect (Ozcelik et al., 2009; Stark et al., 2018). Hence, we confirmed that color coding can promote programming learning in multimedia learning.

Color-coded materials minimize unnecessary search processes used to correlate verbal information, which may help improve performance. Our results show that the fixation duration on color-coded material was shorter than that on grayscale material. This indicates that participants are able to search for associated elements between visual and verbal information more quickly in the color-coded format than in the grayscale format. Utilizing the same color to relate elements in a slide could guide learners to focus on the salient and relevant information

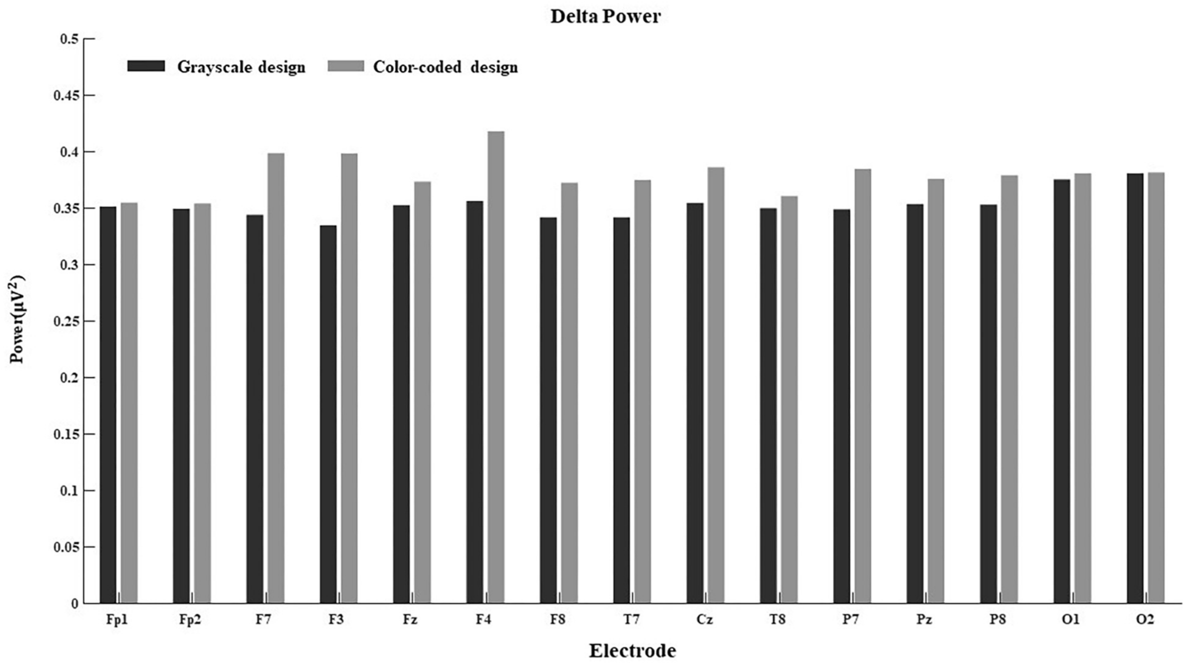


**FIGURE 4 |** Delta power for the 15 electrodes in the grayscale and color-coded conditions while watching video lectures.

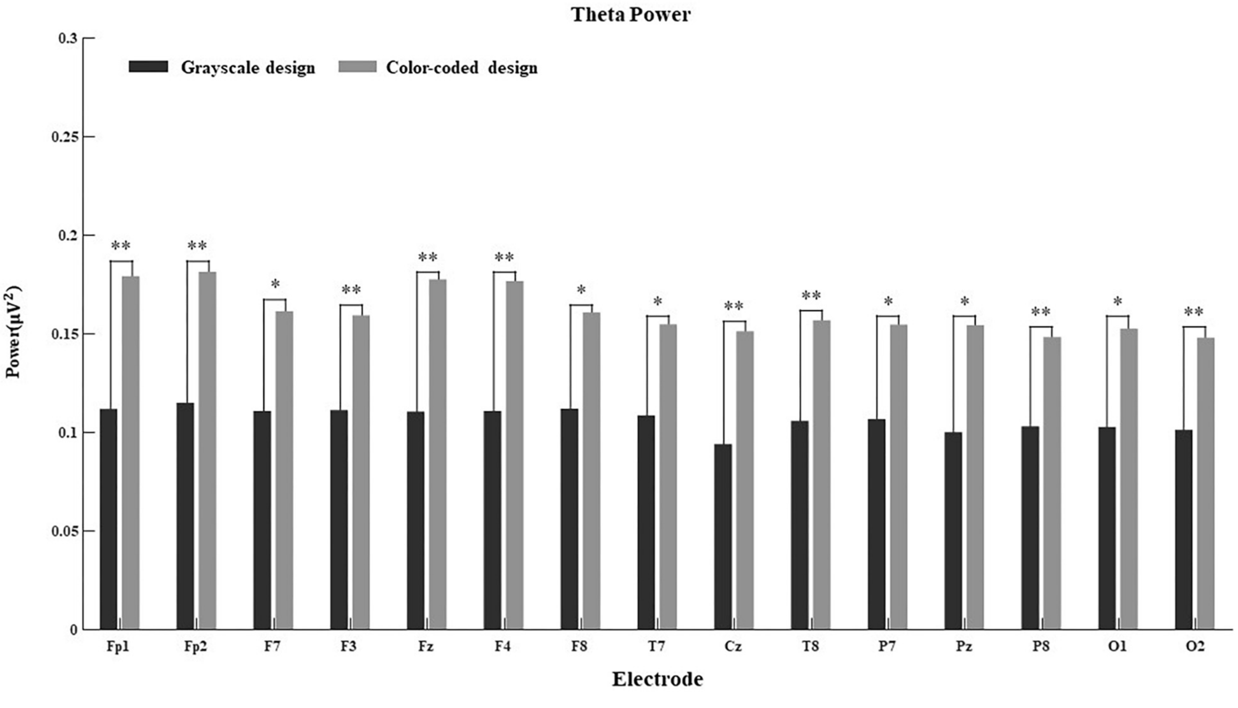


**FIGURE 5 |** Theta power for the 15 electrodes in the grayscale and color-coded conditions while watching video lectures (*$p < 0.05$, **$p < 0.01$).

(Navalpakkam et al., 2005). This is because salient stimuli can automatically capture attention and affect the perceptual choice of subjects when processing information, so as to shorten the information search time and release more cognitive resources for information integration and material organization (Mayer, 2005b; Schnotz, 2014).

The current results are in line with the temporal contiguity effect in multimedia learning (Mayer, 2014). Our data provide

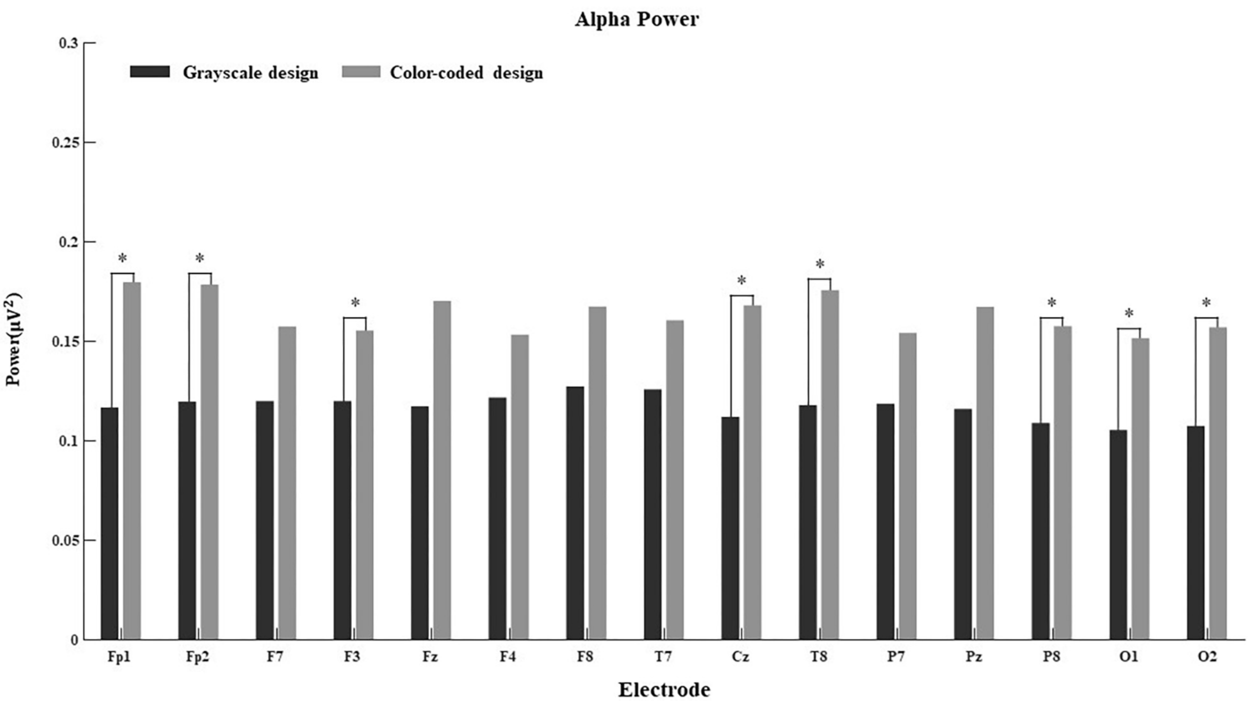


**FIGURE 6 |** Alpha power for the 15 electrodes in the grayscale and color-coded conditions while watching video lectures (*$p < 0.05$).

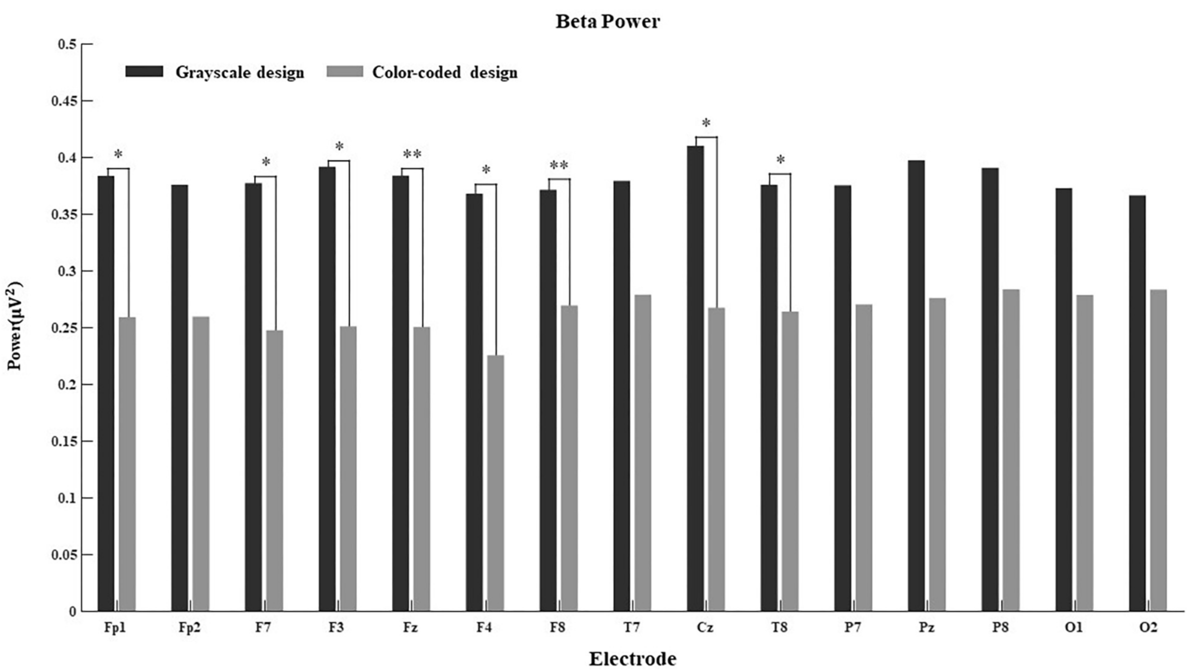


**FIGURE 7 |** Beta power for the 15 electrodes in the grayscale and color-coded conditions while watching video lectures (*$p < 0.05$, **$p < 0.01$).

evidence that color coding helps to form an association between verbal and program code representations because the items processed timely are related to each other (Raaijmakers and Shiffrin, 1981; Kahana, 1996). Color coding facilitates the identification of corresponding visual and verbal elements, and improves learning performance through the temporal proximity of relevant information (Ginns, 2006).

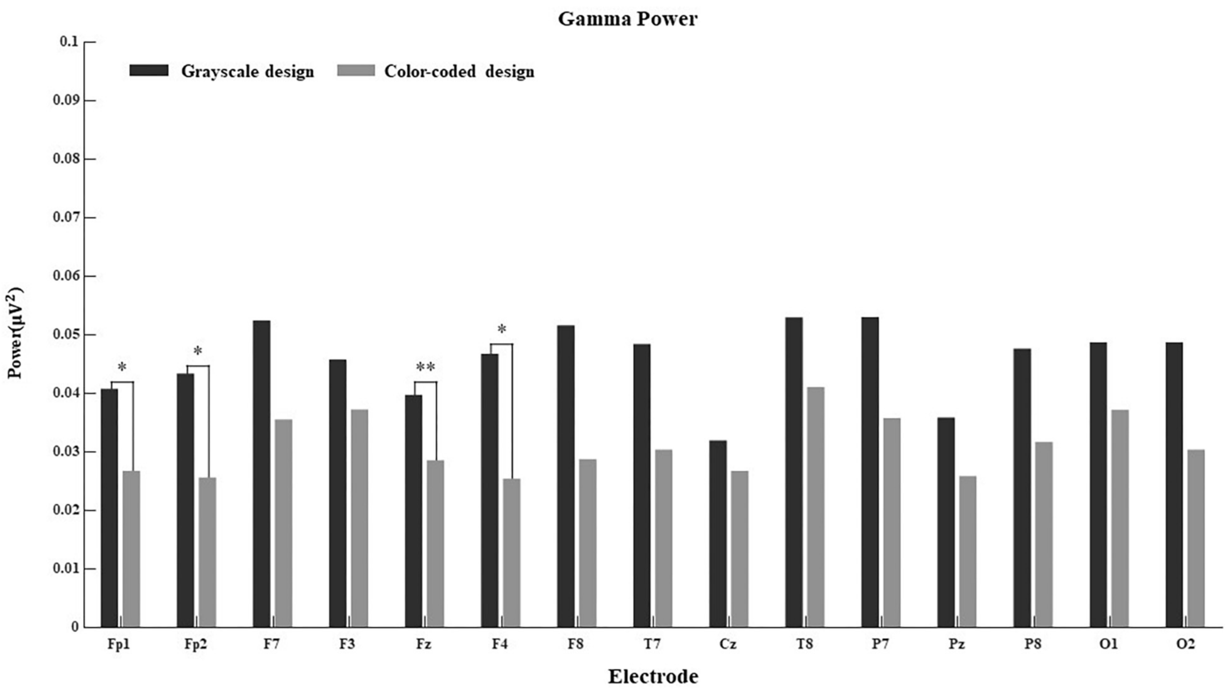


**FIGURE 8 |** Gamma power for the 15 electrodes in the grayscale and color-coded conditions while watching video lectures (*$p < 0.05$, **$p < 0.01$).

**TABLE 5 |** Means and standard deviations of spectral entropy variables.

| | Color-coded group (*N* = 19) | | Gray-scaled group (*N* = 19) | |
|---|---|---|---|---|
| **Dependent variable** | ***M*** | ***SD*** | ***M*** | ***SD*** |
| Approximate entropy | 1.19 | 0.093 | 1.44 | 0.10 |
| Sample entropy | 0.60 | 0.43 | 0.66 | 0.044 |
| Wavelet entropy | 2.13 | 0.019 | 2.14 | 0.018 |

When learners are able to easily ascertain relevant information and integrate verbal and visual information, they can engage more deeply in the cognitive processing required for meaningful learning (Mayer and Chandler, 2001; Mayer and Moreno, 2003; Seufert, 2003). The present study observed higher theta and alpha powers in the color-coded learning conditions than in the grayscale learning conditions. The theta band is related to the working memory. The increases in theta oscillations are related to high working memory activity as well as successful memory encoding (Miller et al., 2018) and retrieval (Solomon et al., 2019; Pi et al., 2021). Therefore, deep processing of learning material in working memory can successfully encode memory (Khader et al., 2010; Lin et al., 2017), and working memory maintenance can forecast long-term memory (Hsieh and Ranganath, 2014). The learners who successfully memorized learning materials showed higher theta power than those who did not (Khader et al., 2010). Neural oscillations in the alpha band are related to an increase in internal attention-demanding cognitive processing (Klimesch, 2012; Fink and Benedek, 2014). Our study suggests that the color-coded group had a greater engagement of working memory and attention than the grayscale group, allowing information to be processed at a deeper level and thus resulting in better learning performance (Pi et al., 2021).

Fixation durations within the same activity can also reflect cognitive processing and cognitive load (Kruger and Doherty, 2016); a longer fixation duration suggests an increased cognitive load. Furthermore, the higher the difficulty of text comprehension and the greater the memory load during learning, the greater the pupil enlargement (Kahneman and Beatty, 1966, 1967). The results of the present study showed that the participants who viewed grayscale video lectures had longer fixation durations and greater pupil size than those who viewed color-coded video lectures. This indicated that the participants under the grayscale learning condition had a higher cognitive load than those under the color-coded condition. These results are consistent with the Cognitive Load Theory (Sweller, 1988, 1994) and the Cognitive Theory of Multimedia Learning (Mayer, 2005b). In the process of multimedia learning, learners need to psychologically integrate information transmitted through external representations into a coherent psychological representation. If learners utilize their limited cognitive resources to search the text when they hear new words in the narration, the visual scanning activity will produce extraneous cognitive processing (Paas and Sweller, 2014; Wang et al., 2020). Prior research has shown that learners usually need instructional support to identify correspondences and establish connections between them (e.g., Seufert, 2003; Seufert and Brünken, 2006). As a mode of signaling, color coding could guide learners' attention toward essential material and thereby eliminate the need to process irrelevant material. Color coding highlights the organization of the essential material to guide learners' cognitive processing. Specifically, it reduces extraneous mental processing demands to allow people to learn more deeply, which in turn leads to improved learning performance.

Using color coding could reduce the search for reference in the text and improve split-attention effects, resulting in lower perceived task difficulty (Ayres and Sweller, 2014; Xie et al., 2016), which is a reliable measure of extraneous cognitive load (Kalyuga et al., 2000). Subjective ratings of task difficulty increase as the extraneous cognitive load increases (Paas and van Merrienboer, 1993; Paas et al., 1994). The study results indicate that the participants in the grayscale group had more extraneous cognitive load than the participants in the color-coded group. Extraneous cognitive load is caused by the inappropriate presentation of the learning material (Sweller, 2004). When the extraneous cognitive load is increased, the germane cognitive load is reduced and learning is lessened. Learners use limited working memory resources to deal with the extraneous factors imposed by the teaching process rather than the intrinsic material. The more working memory resources are needed to deal with the extraneous cognitive load, the less resources are available to deal with the intrinsic cognitive load, which in turn reduces learning (Sweller, 2010). Meanwhile, color coding is an effective multimedia design method that minimizes extraneous overload (van Gog, 2014); it helps people study more deeply in multimedia learning because the added cues emphasize the organization of the essential material. The results indicated that the index $\beta/(\theta + \alpha)$ could measure the extraneous cognitive load during the learning process.

The results also provide evidence for the emotional design hypothesis (e.g., Mayer and Estrella, 2014; Plass et al., 2014). Making essential elements visually appealing (i.e., colored) directs cognitive processing (i.e., selecting) in the learning process by guiding attention, maintaining cognitive processing, and helping learners better understand the essential material (i.e., organizing and integrating) – thereby leading to better learning (Pekrun, 2006).

## CONCLUSION

This study provides evidence for the benefits of using color coding in programming learning during multimedia learning. We utilized multimodal physiological measures to access process information for a detailed analysis of the programming learning process using color-coded design and grayscale design in multimedia learning materials. We likewise combined EEG frequency band power data and eye tracking data to measure mental processing. The results demonstrate that color coding guides learners in finding corresponding visual and verbal information and paying attention to critical information for meaningful learning. The participants under the color-coded condition had a lower cognitive load, more positive learning experience, and better learning performance than those under the grayscale condition.

The results of the present study suggest that using color coding to highlight the format of program code in video lectures for programming learning can improve learning performance. Learning material might be better designed to help learners select relevant information and integrate verbal and visual representations so as to enhance learning (Mayer and Fiorelle, 2014). The conclusions of this study can also be extended to other courses.

## 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 below: https://github.com/zeron21/Multimodal_Data.git.

## ETHICS STATEMENT

The studies involving human participants were reviewed and approved by the Ethics Committee of the School of Information and Electronic Engineering, Zhejiang University of Science and Technology. The 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.

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# Cognitive Ability and Self-Control's Influence on High School Students' Comprehensive Academic Performance

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This study uses a hierarchical linear model (HLM) to examine the effects of cognitive ability and self-control on comprehensive academic performance among students in a high school in Beijing. The study included 572 participating students, including 291 boys and 281 girls, ranging in age from 16 to 18 years old. In this study, the individual level of students' cognitive abilities are used as the first-level variables, including memory ability (MA), information processing ability (IPA), representation ability (RA), logical reasoning ability (LRA), and thinking transformation ability (TCA). Consider self-control at the class level as the second-level variable. The research results show that the five cognitive abilities have a significant positive impact on comprehensive academic performance. Self-control plays an active role in regulating the relationship between RA, LRA, TCA, and comprehensive academic performance.

**Keywords: cognitive ability, self-control, comprehensive academic performance, hierarchical linear model, interactive influence**

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## INTRODUCTION

Zhao (2017) believes that academic performance refers to the performance of students' learning effects after a period of learning of knowledge and skills. Under the current education system, schools often express students' academic performance in the form of examinations. Liu (2019) believes that academic performance, especially college entrance examination scores, affects students' future development, and clarifying the factors affecting academic performance will undoubtedly be of great help to each student's study. Yang (2020) believes that academic performance, as a test of students' learning results, reflects students' mastery of the knowledge they have learned, and is a key indicator to measure students' learning. Li (2019) believes that academic performance is the academic knowledge and skills acquired after learning and training, and it is a concentrated expression of students' learning status and level. Under the current education system in China, academic performance is a measure of a student's learning achievements and important parameters for further studies. Therefore, academic performance is an important indicator for evaluating the learning effects of students.

Cognitive ability and self-control are always important factors affecting students' academic performance (Liang et al., 2020), especially since the adoption of online teaching in the post-pandemic era. Self-control has become a key factor affecting students' academic performance (Schulz, 2021), but it is not clear how cognitive ability and self-control together affect the comprehensive academic performance of students. This research takes high school students' individual-level cognitive abilities and class-level self-control abilities as the research variables, and explores the mechanism of their influence on comprehensive academic performance and the impact of their interaction on comprehensive academic performance.

## The Impact of Cognitive Ability on Academic Performance

Cognitive ability has an important restrictive effect on whether young people can achieve academic success. Cognitive ability refers to the ability of the human brain to process, store, and extract information, including attention, memory, and reasoning ability. It is a key psychological element for people to successfully complete an activity (Sternberg and Sternberg, 2009). Cognitive ability is currently one of the most researched and stable predictors of academic performance (Stadler et al., 2016). Previous studies have focused on the direct impact of individual-level cognitive ability on academic performance (Kuncel et al., 2004; Miriam et al., 2011). In a study of 4,749 junior high school students by Xu and Li (2015), it was found that selective attention, short-term memory, and reasoning ability are significant predictors of language and mathematics performance. Reasoning ability directly affects academic performance, while selective attention and short-term temporal memory indirectly affect academic performance through reasoning ability. Rohde and Thompson (2007) found that cognitive ability directly predicts academic performance, and the correlation is as high as 0.38. Cognitive ability and academic performance in language and mathematics have a moderate to high degree of correlation, which can explain the larger component of variation in academic performance (Deary et al., 2006; Rohde and Thompson, 2007; Plomin, 2011). Deary et al. (2006) conducted a 5-year follow-up study of more than 70,000 British children and found that the correlation between general cognitive ability at 11 years of age and academic performance at 16 years of age was 0.81. The strongest predictive ability can explain 58.6 and 48% of the variation in the dependent variable, respectively. These research findings also support the information processing theory (Deary et al., 2006; Rohde and Thompson, 2007; Xu and Li, 2015), which states that the higher the students' cognitive ability, the faster and more accurately they can pay attention to key information, efficient memory coding, and the output of more effective information, thus leading to higher academic performance (Liu and Wang, 2000; Zhang and Zhang, 2011). In contrast, if the overall level of cognitive ability is low or a certain cognitive ability is lacking, part of the information will be lost in the process of information processing, reducing the output of effective information, and leading to lower academic performance (Miriam et al., 2011). Chen (2016) believes that cognitive abilities have an impact on high school students' chances and choices for further studies. Students with higher cognitive abilities are more likely to attend regular high schools, and conversely, students with lower cognitive abilities are more likely to attend vocational schools. Based on previous research results, cognitive ability often plays a significant role in the achievement of higher academic performance.

Although the relationship between general cognitive ability and academic performance can better reflect the closeness of the two, it is difficult to deeply reflect the inner relationship between them. In fact, "in the learning context, cognitive ability is very important in human learning activities, which can be reflected in a deeper level by including specific cognitive abilities in the scope of the investigation," (David, 2005) because learning activities not only involve different specific abilities, but are also related to how these different abilities work together. Throughout different studies, there is much controversy over the influence model of cognitive ability on academic performance (Formazin et al., 2011). Zhang (2008) found that the correlation coefficients between logical reasoning ability (LRA), Chinese language, and Mathematics scores were all around 0.3, while the thinking transformation ability (TCA) was not significantly correlated with the scores of the two subjects. However, Xu and Li (2015) found that thinking TCA has a significant correlation with performance in the two subjects, and the correlation coefficient between representation ability (RA) and the performance of Chinese and Mathematics is between 0.4 and 0.5. These results confirm that it is difficult to comprehensively and systematically reveal the complex interaction of individual cognitive factors on academic performance when only examining the impact of a single dimension of cognitive ability on a single academic performance. Moreover, previous studies tended to study the influencing factors of cognitive ability on a single subject, and there is a lack of research on the influencing factors of cognitive ability on the comprehensive performance of multiple subjects.

Therefore, this study combines the classification of cognitive ability by Wo (2000); Xu and Li (2015), and Liang et al. (2020), these three researchers have conducted a lot of research and exploration on the five cognitive abilities of working memory, information processing, logical reasoning, representation, and thinking transformation in the article, and obtained scientific and effective research conclusions, and summarized different types of recognition. The test method of knowledge ability. In particular, Wo has developed a software system for measuring these five cognitive abilities. The number of students measured in mainland China has exceeded 2 million, and he has obtained normative data applicable to local students in mainland China. Reliability and validity have been fully tested, and can accurately measure the cognitive ability of students. In addition, Wo (2010) applied for and obtained a Chinese invention patent for the cognitive ability assessment system. According to the research of Wo (2010), this research divides the cognitive ability into memory ability (MA), information processing ability (IPA), RA, LRA, and thinking conversion ability (TCA). It explores the specific impact of different cognitive abilities on the comprehensive academic performance of the three subjects of Chinese, mathematics, and English, and put forward the following hypotheses:

Hypothesis 1a: Memory Ability (MA) in Individual Cognitive Ability of Students is positively correlated with comprehensive academic performance.

Hypothesis 1b: Information processing ability (IPA) is positively correlated with comprehensive academic performance.

Hypothesis 1c: Representation ability (RA) is positively correlated with comprehensive academic performance.

Hypothesis 1d: Logical reasoning ability (LRA) is positively correlated with comprehensive academic performance.

Hypothesis 1e: Thinking conversion ability (TCA) is positively correlated with comprehensive academic performance.

## The Influence of Self-Control on Academic Performance

People have emphasized the important role of cognitive ability factors in the learning process (Kuncel et al., 2004; Miriam et al., 2011; Stadler et al., 2016). In China, many scholars have conducted research on students' academic performance and Cognitive ability, and the general public generally recognizes that students with strong Cognitive ability have good academic performance (Zhang, 2008; Xu and Li, 2015; Chen, 2016). However, a series of studies have shown that intelligence is only one of the factors that determine students' academic performance (Shao, 1983). An individual's academic performance is not only determined by one aspect of his or her state, but is also affected by his or her overall positive mental state.

Self-control refers to the ability of individuals to consciously restrict and manage their own cognition, emotions and behaviors in accordance with social standards or their own wishes without external supervision and external restrictions (Xie, 2009). Duckworth and Seligman (2010) and other scholars have studied the influence of discipline on academic performance, Self-control has a positive effect on the performance of eighth-grade students in the United States. Dai (2013) conducted related research on the relationship between self-control, emotional stability, and academic performance in junior high school students and found that there was a significant positive correlation between the self-control of high school students and their academic performance. Zhao (2017) and others conducted research on the relationship between self-control and academic performance in upper primary school students and found that self-control can significantly predict academic performance. Wang (2003) used a self-compiled self-control questionnaire to study the relationship between the self-control ability and academic performance of middle school students, and surveyed 885 students from the first to second year in Shanghai. The results show that the self-control ability and academic performance of middle school students are Significantly positive correlation. Wang (2004) did a research on the relationship between self-control and academic performance of Mongolian and Han junior high school students. The study surveyed 622 junior high school students. The results showed that there is a significant positive correlation between the self-control ability of junior high school students and academic performance. Previous studies have shown that students' self-control is related to academic performance. However, the mechanisms of the influence of self-control on the academic performance of high school students is still unclear. Existing research rarely study the influence of the two dimensions of cognitive ability and self-control on academic performance at the same time. Based on the shortcomings of existing research, this research will establish a more comprehensive model to study the impact of high school students' cognitive ability and self-control on academic performance. Taking into account the nested structure of the data, a hierarchical linear model (HLM) was selected for analysis. Based on this, the following hypotheses were proposed:

Hypothesis 2a: Self-control moderates the relationship between Memory Ability (MA) and comprehensive academic performance, such that the relationship is stronger for higher levels of self-control.

Hypothesis 2b: Self-control moderates the relationship between Information processing ability (IPA) and comprehensive academic performance, such that the relationship is stronger for higher levels of self-control.

Hypothesis 2c: Self-control moderates the relationship between Representation ability (RA) and comprehensive academic performance, such that the relationship is stronger for higher levels of self-control.

Hypothesis 2d: Self-control moderates the relationship between Logical reasoning ability (LRA) and comprehensive academic performance, such that the relationship is stronger for higher levels of self-control.

Hypothesis 2e: Self-control moderates the relationship between Thinking conversion ability (TCA) and comprehensive academic performance, such that the relationship is stronger for higher levels of self-control.

This study selected students from a high school in Beijing as the participants. The academic performance of the students in this school is at a low level in the Beijing area. Many students have a poor learning attitude and are very irresponsible for their studies. Therefore, self-control ability will greatly affect students' academic performance.

The main research variables and the research relationship are shown in **Figure 1**.

# MATERIALS AND METHODS

## Participants

This study selects 572 students from 50 classes in a high school in Beijing as a sample, with 10–13 students in each class. All students selected in the sample must go to school as normal and have not gone through suspension. At the same time, all students must have been studying in this school since they were in high school, and cannot include transfer students from other regions or schools. Among them, with 291 boys (50.87%) and 281 girls (49.23%), and the age range is 16–18 years old. Among the students, there were 225 in the first year (115 boys and 110 girls), 178 in the second year (83 boys and 95 girls) and 169 in the third year (93 boys and 76 girls). The study included 572 participating students, 291 boys and 281 girls, ranging in age from 16 to 18 years old.

## Procedure

All the tests in this study were conducted on the campus of the Affiliated Middle School of the University of Science and Technology, Beijing. The school teachers uniformly organized all students to enter the computer lab for testing. The test content

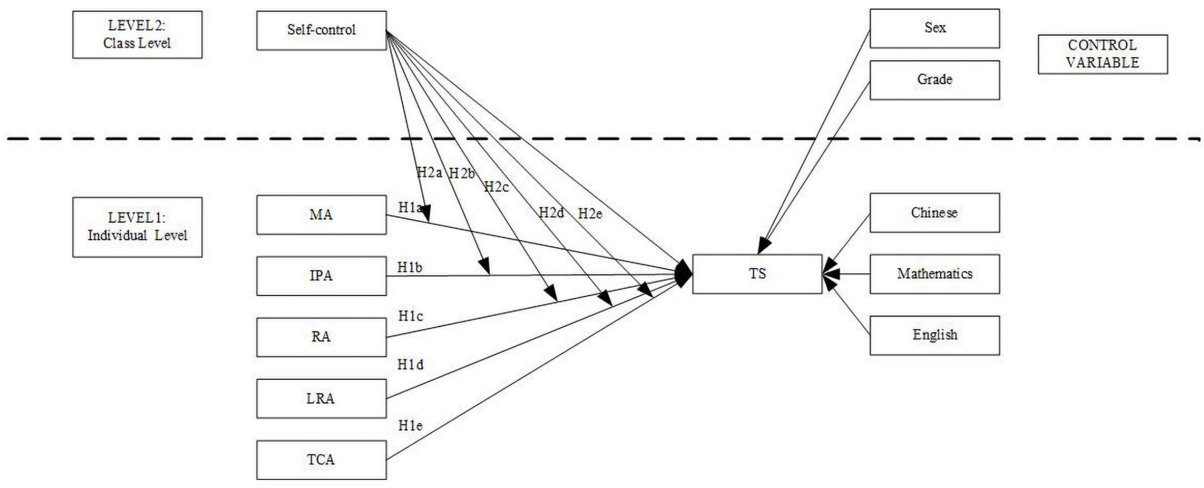


**FIGURE 1 |** Hypothesized model. MA, Memory ability; IPA, Information processing ability, RA, Representation ability; LRA, Logical reasoning ability, TCA, Thinking conversion ability. TS–Comprehensive Academic performance.

included high school students' cognitive ability and self-control tests. The overall duration of the test was 2 h and 30 min. This research was approved by the Research Ethics Committee of the School of Humanities and Social Sciences, University of Science and Technology, Beijing, we obtained written informed consent from all students and their parents before the test, and the data used in the study were provided by the Affiliated Middle School of the University.

## Measures

### Cognitive Ability

The cognitive ability test uses the stimulus information cognitive ability value test system developed by Wo (2010).

The Stimulus information cognitive ability value test system used the world's leading EEG ultraslow fluctuation analyzer and ASL504/501 eye trackers as basic research methods, started from the brain mechanisms of individual psychological development, combined laboratory experiments and field experiments, adopted subtraction reaction time and addition reaction time (accurate to the nanosecond), microgenetics and other technologies, used a form of microcomputer manual operation that greatly improves the discrimination and accuracy of test results, and used the accumulated sample norms of more than 2,000,000 people to make the subjects' personal quantitative indicators comparable to people of the same age.

The test questions of IPA include three parts: image selection reaction, graph comparison reaction, and image matching reaction. The test questions of memory ability are two parts: digital forward, reverse memory, and image matching reaction. The test questions of RA include three parts: spatial image manipulation, spatial image reasoning, and spatial image comparison. The test subject of thinking TCA is a text-picture matching test. The test questions of LRA are conceptual reasoning and logical law reasoning.

The cognitive index analysis method provides the subject with visual, auditory, and/or tactile stimulation information through a stimulation information-providing device to obtain feedback information generated by the subject according to the stimulation information. The feedback information is collected and/or received by the information input device and the information collection device and then sent to the analysis and processing device for analysis so that the analysis and processing device obtains random feedback information subconsciously generated when the subject receives the stimulus information collected by the information collection device. The first analysis data were used to assist in correcting the second analysis data obtained from the inherent feedback information directly put in by the subject through the information input device so that the analysis and processing device determined the subject's performance based on the first analysis data and the second analysis data. A standard score model (Z-score model) was established based on the current cognitive index value for the subject and the average index value for the group. We calculated the Z score of each index item for the subject. In the same way, average response accuracy was calculated based on the data in the response accuracy database. A Z-score model was established based on the current subject's response accuracy and the average value, and the subject's response accuracy Z-score was calculated. Finally, the abovementioned cognitive index value Z score and reaction accuracy Z score were added to obtain a comprehensive Z score. The comprehensive Z score is converted into a T score that characterizes the subject's cognitive ability. The T score is the quantitative measurement of cognitive ability. The cognitive ability values obtained by this test method are centered at 100 and have a normal distribution trend in the range of $\pm$ 50, which has high discrimination validity. Cronbach's alpha in this study ranged from 0.80 to 0.90.

### Self-Control

The Self-Control test scale for middle school students was designed by Zhang et al. (2005). We set up six questions for the test, including a reverse question. The Positive problem was evaluated on a 5-point Likert scale: 1 (Very inconsistent), 2 (relatively inconsistent), 3 (uncertain), 4 (Relatively consistent), and 5 (Very consistent)—this test will test the score of each item. The test set up reverse questions (R), and the reverse questions are set to 5 (Very inconsistent), 4 (relatively inconsistent), 3 (uncertain), 2 (Relatively consistent), and 1 (Very consistent). For example, the scores of each item for self-control are recorded as A1, A2, A3, A4, A5, and A6, where A4 is the reverse-scored question. Then, the total score for self-control is A = (A1+A2+A3+A4+A5+A6)/6. Then the calculated total score is converted into a Z score based on the mean and standard deviation, and then the Z score is converted into a T score with an average of 50 and a standard deviation of 10, then the T score is the test student's self-control ability value. The Cronbach $\alpha$ coefficient of each dimension of the scale is between 0.60 and 0.93, and the test-retest reliability is 0.85. The validity is 0.91.

### Comprehensive Academic Performance

This research takes students' recent test scores as their comprehensive academic performance. Because students choose different subjects, this research only selects the compulsory subjects of Chinese, Mathematics, and English for all students. In order to reduce the impact of different levels of difficulty of examination questions in different grades on the research results, the student scores used in this study are obtained based on the percentage of students' rankings. The calculation formula is: score = (total number of students-student ranking)/total number of students*100. The score range is 0–100. The total scores of the three subjects were accumulated.

## Data Analysis

The data of this study involves two dimensions of students' individual level of cognitive ability and class level of self-control, and there is a level of interaction. The multilevel data structure can be used in the traditional multiple linear regression model. For example, the basic assumption of the ordinary least squares (OLS) method is linear and positive. However, it is obvious that multi-level data cannot satisfy the independence of the same variance and random error terms, which reduces the accuracy of the model results. Compared with OLS, HLM is more suitable for processing multi-layer structure data, decomposing the original single random error to the corresponding levels, which can greatly improve the effect of model fitting (David, 1997); at the same time, decomposition of the total variation of the dependent variable into different levels of variation, systematic analysis of the influence of different levels of variables on the dependent variable, and cross-level interactions are performed in order to obtain more accurate estimation results.

In this study, the cognitive ability of students at the individual level is regarded as the first level of the hierarchical linear regression model, which includes five variables; the self-control at the class level is the second level, which includes one variable. SPSS 19.0 and HLM software were used for data analysis.

The progression of the HLM analysis is as follows: first, do not bring any level of variables into the zero-model test to determine whether the data is suitable for HLM analysis; second, bring in the first level of cognitive ability variables (random coefficient model), and analyze the impact of cognitive ability on academics; third, only the second-level self-control variables (intercept model) are introduced to analyze the individual effect of self-control on comprehensive academic performance. Finally, the first-level cognitive ability and the second-level self-control abilities are brought into the regression equation (full model) to analyze the impact of the interaction between cognitive abilities and self-control on comprehensive academic performance (Goldstein, 2010).

# RESULTS

## Descriptive and Bivariate Analyses

The mean values, standard deviations, and intercorrelations of the variables are presented in **Table 1**. The five cognitive abilities were significantly correlated with comprehensive academic performance (TS): thus, Hypothesis 1a-1e were supported. The self-control showed a significant negative correlation with TS.

## Hierarchical Multiple Regression Analysis

### Zero Model

Before performing HLM, it is necessary to determine whether this method is suitable for use. Generally, it is necessary to test the consistency within a group and the differences between groups. In a HLM, a zero-model analysis must be performed first. The zero-model does not contain any predictor variables and is mainly used to test whether it is necessary to use a multilevel model for analysis and to calculate the influence of high-level factors on the dependent variable. See the **Supplementary Material** for the formula.

The dependent variable $TS_{ij}$ represents the total score for student i; $\beta_{0j}$ is the intercept, which represents the average score of class j students; $\gamma_{ij}$ represents the variation of class j student i around the average score of class j (individual-level random effect), and the variance is $\sigma^2$; $\gamma_{00}$ is the mean of all students' performance; $u_{0j}$ represents the variation in various mean values around the overall mean (random effect at the regional level); and the variance is $\tau_{00}$. In this way, the variation in the dependent variable is decomposed into intragroup and intergroup variations. By calculating the proportion of intergroup variation in the total variation, the magnitude of the influence of the regional level on the dependent variable can be obtained.

In the zero-model, the most important value is the interclass correlation coefficient ICC (1) (intraclass correlation), ICC (1) = $\tau_{00}$ /($\sigma^2$ + $\tau_{00}$). In addition, Keith (1988) believes that when ICC (1) is greater than 0.138, it is considered to be a high correlation. By calculating ICC (1) = 0.333 > 0.138 in this study, it was found that 33.3% of the variance in students' comprehensive academic performance was caused by the differing self-control of students. The general linear regression model is not suitable for a unified analysis of the results of this study. It is necessary to use the HLM model in order to analyze the inconsistency of the differences between the groups. ICC (2) characterizes the degree of difference between the dependent variables in different groups, indicating the reliability of the model. In this study,

**TABLE 1 |** Means, standard deviations, and intercorrelations for variables.

| | M | SD | 1 | 2 | 3 | 4 | 5 | 6 | 7 |
|---|---|---|---|---|---|---|---|---|---|
| 1.MA | 104.85 | 15.91 | – | | | | | | |
| 2.IPA | 102.25 | 13.32 | 0.156** | – | | | | | |
| 3.RA | 106.20 | 7.31 | −0.033 | 0.205** | – | | | | |
| 4.LRA | 103.16 | 9.99 | 0.039 | 0.074 | 0.084* | – | | | |
| 5.TCA | 94.09 | 17.40 | 0.171** | 0.400** | 0.338** | 0.074 | – | | |
| 6.SELF-CONTROL | 106.31 | 15.68 | 0.311** | 0.455** | 0.264** | 0.225** | 0.531** | – | |
| 7.TS | 160.50 | 58.08 | 0.551** | 0.647** | 0.432** | 0.350** | 0.755** | 0.667** | – |

*N = 572. *p < 0.05; **p < 0.01.*

ICC (2) = 0.821 > 0.70 (James, 1982), indicating that students' comprehensive academic performance is in the different self-control groups of students. Since there are significant differences between the two, it is suitable to use the HLM model for analysis. The results of the analysis are presented in **Table 2**.

At the same time, because the student's self-control values used in this study are derived from the questionnaire, where each index value is aggregated from six questions, the aggregation degree of the index should be verified before the analysis. In order to verify that the data have homogeneity within a group and the degree of interrater agreement between different evaluators, the calculated $Rwg_j = 0.864 > 0.7$ in this study (James et al., 1984), which shows that the deviation between the $Rwg_j$ value of students' self-control and the mean value is small, the index has a good degree of aggregation, and the aggregation index formed by each item is reasonable.

## Full Model

The values of cognitive ability, self-control, and interaction items are brought into the model, and grade and gender are used as control variables to analyze the influence of cognitive ability and self-control on comprehensive academic performance. See the **Supplementary Material** for the formula.

Here, $\gamma_{31}$ and $\gamma_{71}$ are the slopes at which the learning attitude of level-2 intercepts the slopes of the respective variables in the first level. In the complete model, the fixed effects include the total intercept, base cognitive ability, self-control, and the interaction of these two levels. The random effect, $u_{0j}$, also represents the randomness of unobserved or unobservable self-control. The effect, $u_{3j}$ -$u_{7j}$, represents the part of the influence of cognitive ability on the dependent variable that varies with self-control and cannot be explained by the group variable included in the model. The results of the analysis are presented in **Table 3**.

In the case of grade and gender as the control variables, MA, IPA, RA, LRA, and TCA have a significant positive impact on comprehensive academic performance (TS) ($P < 0.001$), indicating that Hypotheses 1a, 1b, 1c, 1d, and 1e are supported.

Self-control has a significant positive effect on comprehensive academic performance (TS) ($\gamma_{01} = 2.485, P < 0.001$). However, the grade has a significant effect on students' comprehensive academic performance ($\gamma_{20} = 6.256$, $P < 0.001$), indicating that the relationship between self-control and students' comprehensive academic performance is affected by the age of students.

Self-control plays a positive regulatory role in the relationship between IPA and comprehensive academic performance (TS) ($\gamma_{41} = 0.04$, $P < 0.1$), indicating that Hypothesis 2b is

**TABLE 2 |** Zero model regression results.

| Fixed effect | Coefficient | S.E. | df | *T*-ratio | *p* |
|---|---|---|---|---|---|
| Intercept | 162.795609 | 5.486905 | 49 | 29.670 | 0.000 |
| Random effect | S.E. | Variance | df | Chi-square value | *p* |
| $u_0$ | 35.51330 | 1261.19434 | 49 | 249.33555 | 0.000 |
| $\gamma_{ij}$ | 50.30352 | 2530.44419 | | | |

**TABLE 3 |** Hierarchical linear model regression results.

| Fixed effect | | Full model | |
|---|---|---|---|
| | | Coefficient | S.E. |
| | Intercept $\gamma_{00}$ | 1150.717414*** (0.000) | 2.287450 |
| Control variable | GRADE ($\gamma_{20}$) | 5.625206*** (0.000) | 0.540922 |
| | SEX ($\gamma_{10}$) | 0.633757 (0.385) | 0.728651 |
| Cognitive ability | MA ($\gamma_{30}$) | 1.553573*** (0.000) | 0.030501 |
| | IPA ($\gamma_{40}$) | 1.479794*** (0.000) | 0.027549 |
| | RA ($\gamma_{50}$) | 1.553179*** (0.000) | 0.059689 |
| | LRA ($\gamma_{60}$) | 1.520598*** (0.000) | 0.048074 |
| | TCA ($\gamma_{70}$) | 1.493005*** (0.000) | 0.031347 |
| Self-control | Self-control ($\gamma_{01}$) | 2.485198*** (0.000) | 0.127194 |
| Interaction layer | Self-control*MA ($\gamma_{31}$) | 0.02890 (0.302) | 0.02766 |
| | Self-control*IPA ($\gamma_{41}$) | 0.03989* (0.083) | 0.02259 |
| | Self-control*RA ($\gamma_{51}$) | 0.09022* (0.073) | 0.04934 |
| | Self-control*LRA ($\gamma_{61}$) | 0.02510 (0.490) | 0.03606 |
| | Self-control*TCA ($\gamma_{71}$) | 0.3752** (0.037) | 0.02483 |

**P < 0.1; **P < 0.05; ***P < 0.001.*

supported. Self-control regulates the relationship between RA and comprehensive academic performance (TS) ($\gamma_{51} = 0.09$, $P < 0.1$), indicating that Hypothesis 2c is supported. Self-control also plays a positive role in TCA and comprehensive academic performance (TS) ($\gamma_{71} = 0.735$, $P < 0.05$); thus, Hypothesis 2e is also valid.

# DISCUSSION

## Impact of Cognitive Ability on Comprehensive Academic Performance

Previous studies have shown that cognitive ability is a psychological feature and a psychological condition for the normal learning activities (Stadler et al., 2016). In China, elementary and junior high schools belong to the state's compulsory education stage. The school effect of students is not tested or evaluated, and the development of students' learning ability is not paid much attention to. At the high school stage, because students have to take the college entrance examination to enter the university, both teachers and students pay attention to improving academic performance, and also attach importance to the development of students' learning ability. Therefore, the high school stage is a good time for students to effectively improve their learning abilities. Different subjects have different ability requirements for students (Zuo and Wang, 2016; Liang et al., 2020).

MA (memory ability) can effectively help students improve memory, recitation, and other supporting content (Liang et al., 2020). At the same time, it interacts with IPA to improve students' reading comprehension ability. This is particularly evident in Chinese and English reading. Therefore, in students with good MA, academic performance is also better (Yu et al., 2014). RA (representational ability) plays an important role in the learning of spatial knowledge in subjects such as mathematics (Shao et al., 2004). At the same time, RA can also stimulate associative memory to recite Chinese and English related knowledge, which makes students perform better academically (Lin et al., 2003). TCA (thinking conversion ability) is reflected in the speed and accuracy of thought transformation, so any subject learning is inseparable from this ability (Zeng and Xie, 2021). Especially in high school mathematics, students with strong TCA can easily summarize and master ideas and methods of completing new math problems, and proficiently apply them to similar problems, and achieve good comprehensive academic performance (Liu, 1988). LRA is divided into two types: inductive reasoning and deductive reasoning (Zhang, 2008). The influence of LRA on academic performance is mostly concentrated in mathematics (Zhu et al., 2020). In recent years, the examination of students in Chinese and English has also been emphasized with the changes in the content of Chinese examinations. Given the logic and rigor of Chinese and English exams (Hu, 2017), LRA has also been shown to affect the scores in the reading part of the Chinese and English exams. IPA is mainly represented by reading comprehension ability and is also related to the efficiency of listening to lectures (Hu et al., 2010). Higher IPA fosters in students a greater ability to understand and master reading in the classroom, the formation of knowledge systems, and better academic performance in examinations (Yuan and Wen, 2003).

At the same time, it was found that the five cognitive abilities have an impact coefficient of approximately 1.5, that is, each individual ability value increases. Each increase of 1 unit will increase the corresponding comprehensive academic performance by 1.5 points, indicating the balance of the students' examination subjects at this stage. The examination questions focused on the examination of students' comprehensive abilities rather than the investigation of a single factor.

## The Influence of Self-Control on Comprehensive Academic Performance

Self-control is a behavior habit, with self-management as its essence. It refers to the behavioral ability that students can use to force themselves to complete the expected goals that should be accomplished based on certain principles and norms, relying on their own conscience and willpower without supervision (Liu, 2020).

The self-control ability of high school students means that they have higher concentration and the ability to resist external temptations, which can help high school students not to be influenced by the outside world. For high school students, as long as they improve their self-control ability, they can think independently, complete homework, study and reduce time wasting, thereby increasing their learning efficiency and improving their academic performance quickly and continuously.

According to Beijing's teaching characteristics, the school ends at 16:30 in the afternoon, while the remaining time is at the discretion of the students. Students with strong self-control can master the time well and spend a lot of time on learning activities to consolidate their knowledge and improve their studies. Thus, students with high self-control can often invest more time in subject learning and achieve better comprehensive academic performance.

At the same time, compared with cognitive ability, it was found that self-control has a significant and positive influence on comprehensive academic performance. For every additional unit of a student's self-control, their comprehensive academic performance will increase by 2.49 points, which is more effective than any single learning ability. This research shows that the key factor restricting the improvement of students' comprehensive academic performance is self-control, not the student's cognitive ability.

At the same time, in terms of the influence of the control variables of grade and gender, gender had no significant effect on comprehensive academic performance, whereas the effect of grade on comprehensive academic performance is very significant. Each increase in grade increases corresponding comprehensive academic performance by 5.6 points, indicating that with the increase in students' age, students' adaptability and learning methods continue to mature. With the increase of age, students' self-control ability has also been improved (the average self-control ability of the first grade is 102, and the average self-control ability of the third grade is

109). Students in the upper grades can conduct better self-management, are less likely to experience emotional breakdown, and can calmly analyze the reasons and deal with them well when faced with substantial progress or regression in performance (Zheng and Zhang, 2021). At the same time, the emotional state of senior students is relatively stable, and their emotional regulation ability will be higher, and they can better control themselves from being affected by other things, thereby improving learning efficiency and improving comprehensive academic performance.

### The Impact of the Interaction Between Cognitive Ability and Self-Control on Comprehensive Academic Performance

Regarding the interaction between cognitive ability and self-control, it was found that self-control has a positive moderating effect on the influence of IPA, RA, and TCA on comprehensive academic performance. The higher the self-control, higher is a student's degree of concentration; thus, when students go to read and study, the advantages of IPA and presentation ability can be fully utilized to improve the speed of understanding and mastery, thereby improving learning efficiency and comprehensive academic performance (Wang, 2011). Consequently, students with high self-control will invest a lot of time in learning, so that through a lot of exercises, they can exercise the flexibility and divergence of learning thinking, and give play to the advantages of TCA, which will help them in the learning process. Students can continue to sort out, summarize, and master the laws of learning, doing so more efficiently (Wo and Lin, 2000), and improving their comprehensive academic performance.

In addition, it can be seen that the moderating effect of self-control in TCA and comprehensive academic performance is far greater than that of IPA and presentation ability. This is because with the progress of China's examination reform, the importance of examination questions in the assessment of students' thinking has become increasingly important, exceeding the assessment of the mastery of basic knowledge (Lin, 2021).

In addition, MA, LRA, and self-control ability have no significant influence on comprehensive academic performance. This is because MA is a kind of innate cognitive ability possessed by students, which does not change with students' behavior. Therefore, for students with high MA and poor self-control ability, students can quickly complete the memory task and achieve good academic performance without too high self-control ability. LRA is more of a cognitive ability that relies on students' in-depth thinking to improve. The logical reasoning questions in the exam generally require students to spend a lot of time and energy to make it, and students with high self-control ability usually have time arrangements. Integrity and organization (Zheng and Zhang, 2021). They can balance the time arrangement during the examination process, and will not spend a lot of time on logical reasoning questions, so the interactive effect of LRA and self-control ability on academic performance is not significant.

### Limitations and Future Directions

All samples in this study are from a Beijing high school, and the sample size was relatively small. The next step will be to select more schools in other provinces in China for research and comparison. In addition, when considering the factors that affect students' cognitive abilities, this study only considers self-control, and does not use more factors for analysis. The next step will be to analyze the impact of students' planning ability, execution ability, and persistence, and the impact of the project is expected to provide more valuable research results. At the same time, this research only considered high school students in the research process, which has limitations in the age of the research group, next research will expand the age range of the research, from elementary school, junior high school, high school, and university.

## CONCLUSION

This study uses a HLM to study the impact of cognitive ability and self-control on students' comprehensive academic performance. Doing so, it was found that MA, IPA, RA, LRA, and TCA have a significant positive impact on comprehensive academic performance. Self-control has a significant positive influence on comprehensive academic performance, and self-control plays a positive role in regulating IPA, RA, TCA, and comprehensive academic performance. Therefore, in the process of improving students' comprehensive academic performance, we should not only focus on the training of cognitive ability, but also pay attention to cultivating students' self-control ability. Teachers should set clear learning goals for students in the classroom and formulate executable self-control plan. Parents should pay attention to urging students to complete the study plan on time and create a good self-control learning environment for students' learning. Students should also have an active sense of self-control, and cultivate good behaviors with the assistance of teachers and parents, so as to improve their overall academic performance.

## DATA AVAILABILITY STATEMENT

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

## ETHICS STATEMENT

The studies involving human participants were reviewed and approved by the Research Ethics Committee of the School of Humanities and Social Sciences, University of Science and Technology Beijing. Written informed consent from the 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

YS and SQ contributed to conception and design of the study. YS contributed to data collection, performed the statistical analysis, and wrote the first draft of the manuscript. Both authors contributed to manuscript revision, read, and approved the submitted version.

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# A Comparison of the Effectiveness of Online Instructional Strategies Optimized With Smart Interactive Tools Versus Traditional Teaching for Postgraduate Students

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To solve the problem that lack of interaction in online courses affects motivation and effectiveness of students' learning, smart interactive tools were introduced into the online Neurobiology course. This study aimed to evaluate the students' satisfaction with online teaching mode and assess the academically higher and lower performing students' learning effectiveness in the online course optimized with smart interactive tools compared to face-to-face learning. Descriptive statistics and independent *t*-tests were used to describe student samples and determine the differences in students' satisfaction and performance. Reflections of students' satisfaction revealed that about 65.8% were satisfied with the learning involvement and about 60.5% were satisfied with the class interaction. Almost two-thirds of the class agreed that the smart interactive tools applied in the online course could help them attain their learning goals better. Among all the smart interactive functions, the class quiz was the most effective one in helping students grasp the main points of the course. No significant differences were found between the two teaching modes in the overall and academically higher or lower performing students' final exam average scores. Compared to each band score of such two teaching modes, no one failed to pass the final exam in the online course, however, three lower-performing students who were taught in the traditional course failed. This study suggested that optimized online teaching with smart interactive tools could produce the same learning effectiveness for the academically lower-performing students as for the higher-performing students. Meanwhile, the instructors could know the learning status in which each student was and perform personalized guidance and improve exam passing rate accordingly.

**Keywords: online, face-to-face, smart interactive tools, effectiveness, postgraduate course, neurobiology, instructional strategies, interaction**

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## INTRODUCTION

With the rapid progress of the integration of education and information technology in the digital era, the online teaching mode and teaching strategies of postgraduate courses need to be optimized. Compared to the traditional or face-to-face teaching mode, the previous online teaching mode has several problems as follows: (1) Due to the lack of teacher's supervision, it is impossible to ensure that the students would always stay focused in class. (2) Since teacher and students are not in the same space, it is difficult to make real-time interaction. The teacher cannot know whether or not the students understand the teaching content through their facial expressions and feedback. (3) Online teaching has a different but professional requirement for the teaching infrastructure or ecosystem. At present, the application of online teaching tools and MOOC resources has greatly promoted the development of online teaching modes in higher education (Curran et al., 2019; Pozón-López et al., 2021). Much of the research had indicated that compared to face-to-face instructional delivery format, the student evaluation of online courses showed no significant differences both inside and outside the health education field (Riffell and Sibley, 2005; Campbell et al., 2008; Todd et al., 2017; Harwood et al., 2018). For some basic professional courses in science and engineering, which need more hands-on activities and live demonstrations, online teaching still has some issues on students' motivation and effectiveness (Akdemir, 2010). The questionnaire from Tang et al. (2020) showed the undergraduate engineering students were dissatisfied with the communication and Q&A modes in online classes. Moreover, some courses, which required higher cognitive skills of analyzing, evaluating, and creating, such as statistics, might produce poorer test performance to teach online among the students with lower cognitive skills of remembering and understanding (Lu and Lemonde, 2013). For the academically lower-performing students, the lack of face-to-face synchronous interaction of online courses might be the reason for their worse test performance compared to the academically higher-performing students. In addition, studies have shown that online courses that lack substantive and meaningful interaction might generate a sense of isolation, unsatisfying learning experiences, and high dropout rates (Bennett et al., 1999). Therefore, how to solve the lack of interaction in online courses is essential for improving students' motivation and effectiveness in learning.

Recently, technical requirements (e.g., Blackboard, MOODLE, Web 3.0, email, discussion boards, and Internet speed) and learning skills (e.g., motivation, social interaction, and self-discipline) were introduced into online courses to solve the above problems (Cho et al., 2010; Cho, 2012; Aljawarneh, 2020; Müller and Wulf, 2020). Furthermore, some smart interactive tools, such as Rain Classroom and Tencent Meeting, are another technical choice to improve this problem (Lu and Ding, 2020; Zhang, 2020). At present, Rain Classroom has been successfully used for online teaching of different subjects, such as biochemistry and English (Shu et al., 2019; Wu, 2019; Wang and Hu, 2020) and realizes the interaction between the learners and the content, as well as the learners and the instructor. This smart interactive tool not only has various interactive functions, but also has a data analysis function. The data analysis function could help the instructor to grasp the students' learning situation of the course content and to optimize the teaching strategy conveniently through the feedback in time from students' preview and review performance, the quiz answers in and after class, and the final test scores as well. Tencent Meeting is also a widely used interactive tool, which can mainly realize the learner-instructor interaction as well as the inter-learner interaction. The introduction of these smart interactive tools solves the lack of synchronous interaction and feedback, improves the student learning motivation, and makes online teaching in higher education more effective.

Allen and Seaman (2015) pointed out many higher education institutions accepted that online learning is critical to their long-term strategy. Campbell et al. (2008) in their study showed that compared to undergraduate level, graduate students who have higher scholastic aptitude could produce better test performance with an online or hybrid online course. In the postgraduate courses, the online teaching mode will bring the following advantages: (1) Not restricted by the classroom resources and the number of students, and the teaching time can be arranged more flexibly (Peacock et al., 2012). (2) The students could learn using a self-paced and student-centered approach and review the course using the playback function (Ituma, 2011; Kemp and Grieve, 2014). The graduate students studying online are often required to take on greater responsibility for their own learning. Compared to face-to-face learning, students in the online course report feelings of social disconnectedness, missing familiar teacher immediacy, and interpersonal interactions and social cues (Slagter van Tron and Bishop, 2009; Crow and Murray, 2020). Therefore, introducing smart interactive tools into the online teaching of postgraduate courses is worth exploring and practicing. Lamon et al. (2020) proposed that a more active and interactive mode of online teaching provides postgraduate students with a greater sense of inclusion and satisfaction.

During the COVID-19 pandemic in the 2020 spring semester, the adoption of online learning seems to be an abrupt response to the crisis (Bozkurt and Sharma, 2020). Charles et al. (2020) defined this temporary shift of instructional delivery to an alternate delivery mode without the building of a specially designed ecosystem–emergency remote teaching (ERT). The Neurobiology elective course arranged to teach online this spring semester doesn't belong to ERT. Before online teaching, all teachers have received technical training on smart interactive tools since 2019 and designed the online instructional strategies as well. In addition, the instructors also have 1 year experience in blended teaching mode for undergraduates. York et al. (2007) pointed out that many online courses are not designed or delivered with careful consideration of foundational instructional design principles. To improve the interaction and sense of presence, we optimized the instructional strategies, such as reducing the teaching time of one section and distributing some easy course content to preview materials to save more time for interaction with the students. Whether the new smart interactive tools and the optimized instructional strategies might improve the students' effectiveness need to be explored.

To solve the problem that the lack of interaction of face-to-face courses in online courses affects the students' motivation and effectiveness in learning, and then affects student test performance, smart interactive tools were introduced into neurobiology online courses. The aim of this study is to assess the students' satisfaction of the attitude and practice toward the Neurobiology online course optimized with the smart interactive tools and to evaluate the academically higher and lower performing students' learning effectiveness of the two teaching modes. We hope to solve the lack of interaction in online teaching, find out the satisfying online instructional strategies and course design features, and enhance students' learning effectiveness with smart interactive tools.

# MATERIALS AND METHODS

## Study Participants

This study assessed 74 neurobiology students' reflections about the Neurobiology course. Of whom, 38 students were enrolled in the online course, their average age was 27 ± 2.5 years, with ages ranging from 23 to 35 years. Forty-seven percent of students were female. 36 students were enrolled in the traditional course, their average age was 26 ± 2.3 years, with ages ranging from 24 to 31 years. Thirty-three percent of students were female.

## Study Design

This study was intended to examine the effectiveness of the online course design features and instructional strategies optimized with the smart interactive tools from the students' perspective. The teachers of online courses are all professors and associate professors, who have been teaching the traditional face-to-face Neurobiology course for years. They designed the instructional strategies of this online course. The total teaching time of the two teaching modes is the same. The subjects are the postgraduate students who choose this Neurobiology course.

## Context of the Study

The neurobiology course is an elective course offering for all postgraduate students. The theoretical part of this course has been taught offline in the past, with a teaching time of 3 weeks, 12 sections. To cultivate physicians and scientific researchers with a broad neuroscience foundation and solid scientific research skills, the learning objectives of this course are as follows:

- Knowledge goal: To expand and deepen the theoretical knowledge of neurobiology, especially the advanced brain functions, neuroendocrine-immune regulatory network, and related disciplines such as neurology and psychiatry, to know the frontiers of neurobiological development.
- Ability goal: To master the method to establish common central nervous system disease models, to independently conduct scientific research in neurobiology and related disciplines, to promote the translational research of neuroscience.
- Literacy goal: To perform a rigorous scientific attitude, to stick to academic ethics.

The course content includes the molecular mechanisms and research models of the latest advances in learning and memory, Alzheimer's disease, Parkinson's disease, epilepsy, alcohol-related neurologic disorders, and other central nervous system diseases. At the same time, relevant experimental courses were set up for the establishment and evaluation of several brain-disease models, such as the glioma model, cerebral ischemia model, and depression model, etc. So far, the content of experimental courses is not suitable for online teaching. The online teachers, teaching time, teaching purpose, teaching content, and final evaluation of this study are completely consistent with those of traditional teaching.

## Online Smart Interactive Tools

In online teaching, the appropriate smart interactive tools are very crucial to achieve satisfactory teaching effectiveness. Based on the teaching experience of other online courses and the survey of students, the cloud-based Rain Classroom and Tencent Meeting tools were selected to jointly build the online teaching platform of the Neurobiology course. As a plug-in of PowerPoint, Rain Classroom can enable PowerPoint combined with audio/video live broadcast for thousands of people, can also be used to send preview and review materials before and after class, send quizzes, vote in class, and realize real-time interaction with students *via* the functions of the real-time barrage, submission, random roll call, and class bonus. Teachers can also check the students' class participation using the functions of quiz answer time and accuracy rate, partial ranking of outstanding students, and early warning students (**Figure 1**). To realize the online face-to-face interaction through audio and video between teachers and students, Rain Classroom needs to be nested within Tencent Meeting, a cloud-based video conferencing tool. In addition, a WeChat group including the online teachers and students is established. If the students have any questions about any point in the course, they can communicate with the teachers through WeChat privately after class. The Rain Classroom also provides a course playback function for the students who are unable to log into the online class.

## Course Setup

This course was directly binding to the online teachers' personal system of the smart interactive tools by the office of academic affairs. The online teachers built the resource bank and test bank of neurobiology in Rain Classroom, including courseware, preview and review PowerPoint, MOOC, and literature materials, self-made videos, and quizzes, etc. In the offline courses of Neurobiology, each section is approximately 45 min long, with a break of 5 min between two sections. Based on the teaching experience of other online courses and the survey of students, the online teaching time of each section is set up to 30 min, with a break of 5 min to ensure the online learning situation of students. The lack of appropriate and deep interaction between students and teachers is a common issue in online teaching, which may result in a sense of isolation and a high dropout rate (Moore, 1991; Ruth et al., 2015). To increase the interaction between students and teachers in a 30-min section, Rain Classroom provides several functions, such as timed quizzes, voting, real-time barrage, submission of comments, random roll call, and the detailed analyzed data. These functions would be helpful to ensure the students' preoccupation (**Figure 1**).

## Assessment

To evaluate whether the smart interactive tools might improve the learning effectiveness of the academically lower-performing students, according to Garavilia and Gredler (2002) and Lu and Lemonde (2013) method, we subdivided the students in

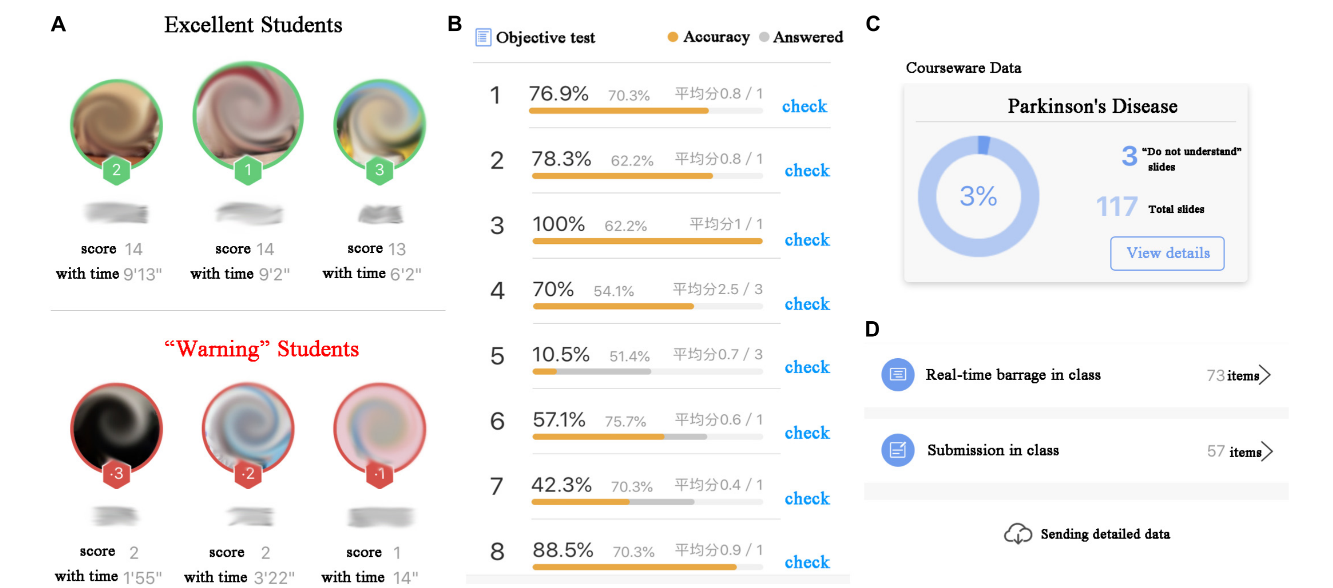


**FIGURE 1** | Part functions of smart interactive tool Rain Classroom. **(A)** Participation in the class quiz. **(B)** Correct rate of quiz answers. **(C)** The courseware data of the students who did not understand a certain slide of PowerPoint. **(D)** The data of the students who posted the real-time barrages, who sent the submission in online class.

each teaching delivery group into academically higher and lower performing students using their assignment marks. The same assignments were given to both online and traditional face-to-face students, which are composed of multiple-choice questions and short answer questions. The assignments were given out once a week for 3 weeks during the course. After the subdivision, we had 18 lower-performing students, and 20 higher-performing students in the online class. In the face-to-face class, there were 17 lower-performing students and 19 higher-performing students. The median assignment mark for each student was computed. Online student assignment median was 85, while face-to-face students had an assignment median of 83.

To improve students' enthusiasm for online learning, the test scores of this course are divided into two parts: formative score accounted for 10% of the total score (including the overall performance of student's preview before class and review after class, class participation, and quiz scores), report writing score accounted for 20% of the total score, and 70% of the final exam score. When comparing with traditional courses, this study only compares the final exam scores due to the different assessment strategies of offline and online courses on the formative score. The final exam paper can be posted online through the Rain Classroom test bank. Rain Classroom also has a function of online invigilation, which is to identify students and supervise the students' answering process through the computer camera.

## Data Analysis

Likert scale rating questions were used to assess students' satisfaction with online courses. Students' satisfaction with the online course of Neurobiology was displayed as proportions. Results were saved and analyzed using GraphPad Prism 7. Descriptive statistics were displayed in percentages and means ± standard error (SE). Comparison of online versus traditional assignment scores and the effectiveness of two teaching modes of Neurobiology course regarding students' course evaluation scores was done using an independent *t*-test and a *P* value of $\leq$0.05 was considered significant.

# RESULTS

## Analysis of the Students' Performance Between Assignments and Final Exam

The correlation between the assignments and final exam performance from both online and traditional face-to-face students was analyzed to ensure the student's assignment score could be used as a categorization method to classify a student's scholastic aptitude. There was a significant correlation of 0.52 and 0.67 between the assignment average score and final exam performance (**Figure 2**). Then, the assignment performance was evaluated to determine if the students of the two-teaching mode had any significant differences in their aptitude for the Neurobiology course. No significant difference was observed in the overall average scores, as well as in the average scores of the lower and higher-performing students between the two teaching modes (**Table 1**).

## Analysis of the Students' Reflections

Reflections of students about online Neurobiology courses using the Likert scale rating (**Table 2**) showed that about 65.8% were satisfied with the learning involvement, and about 60.5% were satisfied with the class interaction. Almost two-thirds of the class (65.8%) agreed that the online course helps them attain the learning goals; 5.3% disagreed and 23.7% could not

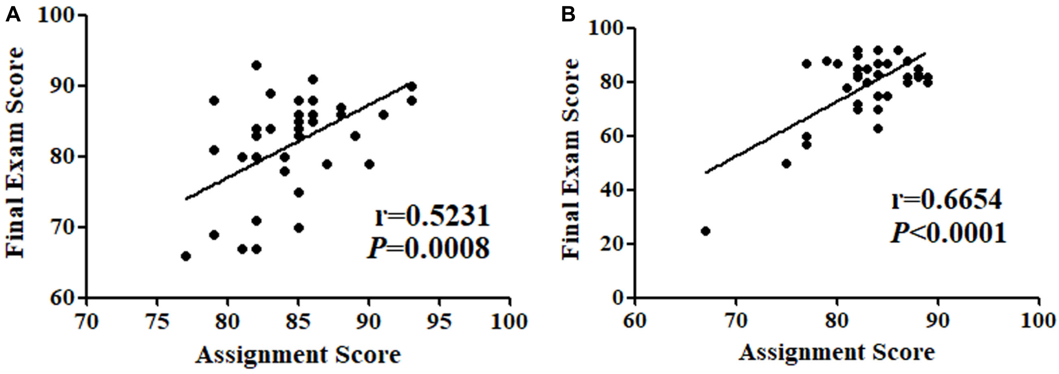


**FIGURE 2 |** Correlation of final exam score with assignment score for online **(A)** and traditional face-to-face students **(B)**.

decide. According to the student reflections, all online interactive functions are helpful. Among them, the class quiz is the most effective one in helping students grasp the main points of the Neurobiology course (**Figure 3**).

## Analysis of the Students' Final Exam Performance

Comparison of the overall and academically lower and higher performing students' final exam average scores of the two teaching modes was done using an independent *t*-test (**Table 3**). Results indicated no significant differences were found between them. In the online group, no one failed to pass the final exam. The student number and average score of the band score from 60 to 69 were higher than those in the traditional group, and these students were all academically lower-performing students. No big differences were observed on the band score above 70 between the two teaching modes. However, in the traditional group, three lower-performing students failed to pass the final exam (**Table 4**).

# DISCUSSION

Online teaching mode has many advantages as we mentioned at the beginning of this article. To better improve online teaching, we optimized it with the smart interactive tools in the postgraduate Neurobiology courses in 2020. To avoid the above-mentioned problems of previous online teaching, we designed a new online instructional strategy combined with our teaching experience from other online courses. To reduce the inability of students to stay focused for a longer time in the online course due to the lack of teacher's supervision, we shortened the teaching time of each section from 45-min offline to 30-min online. During the 30-min period, a variety of interactive functions of smart interactive tools were used, such as class quiz, random roll call, real-time barrage, submission, voting, and "do not understand" button to allow students to actively participate in class. The above functions have all been praised by the students, they agreed these functions would help them better focus on the teaching content.

Lu and Lemonde (2013) in their study showed that students who struggle academically might produce poorer test performance in the online course for the lack of interaction as in traditional courses. The students of higher scholastic aptitude, such as graduate students, had better performance in the online course (Campbell et al., 2008). Although the Neurobiology course offering for postgraduate might require less cognitive skills than some other courses, such as statistics, we sub-divided the students of the two teaching modes into academically higher and lower performing groups using their assignment median scores to compare to the students' learning effectiveness. The data analysis function of the smart interactive tool Rain Classroom is of great help for teachers to know the learning status in which each student is and provide the personalized

**TABLE 1 |** Comparison of online versus traditional assignment scores.

| | Above median Mean (SE) | Below median Mean (SE) | Overall Mean (SE) |
|---|---|---|---|
| Online | 87.20 (0.60) | 81.17 (0.50) | 84.34 (0.63) |
| Traditional | 85.74 (0.47) | 79.47 (0.97) | 82.78 (0.74) |
| *P*-value | 0.06 | 0.13 | 0.11 |
| t-score | 1.91 | 1.56 | 1.62 |
| df | 37 | 24 | 72 |

**TABLE 2 |** Assessment of students' satisfaction about the online neurobiology course.

| | Strongly disagree % | Disagree % | Neutral % | Agree % | Strongly agree % |
|---|---|---|---|---|---|
| Learning motivation | 2.6 | 7.9 | 18.4 | 55.3 | 15.8 |
| Learning involvement | 5.3 | 5.3 | 23.7 | 52.6 | 13.2 |
| Class interaction | 5.3 | 10.5 | 21.1 | 50.0 | 10.5 |
| Understanding of the concepts | 7.9 | 10.5 | 21.1 | 50.0 | 10.5 |
| Completing of the learning tasks | 5.3 | 7.9 | 23.7 | 52.6 | 10.5 |
| Reaching the learning goals | 5.3 | 5.3 | 23.7 | 55.3 | 10.5 |

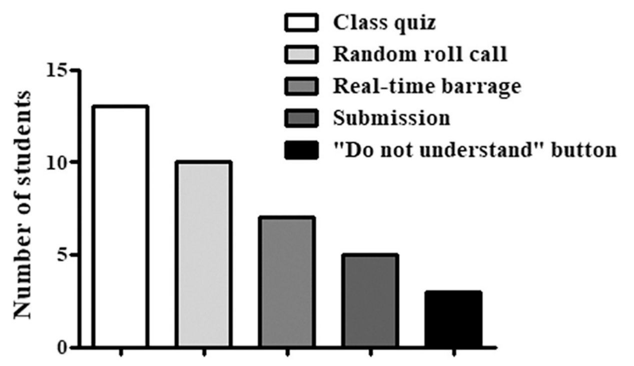


**FIGURE 3 |** The students' assessment of online instructional strategies.

**TABLE 3 |** Comparison of students' final exam average score of the two teaching modes.

| | Above median Mean (SE) | Below median Mean (SE) | Overall Mean (SE) |
|---|---|---|---|
| Online | 84.50 (1.18) | 78.11 (2.00) | 81.47 (1.24) |
| Traditional | 81.63 (1.64) | 74.82 (4.30) | 78.38 (2.24) |
| *P*-value | 0.16 | 0.50 | 0.23 |
| t-score | 1.43 | 0.69 | 1.21 |
| df | 37 | 22 | 54 |

**TABLE 4 |** Comparison of student number and average score on different final exam band score of the two teaching modes.

| Score | Course structure | Mean | N (overall) | N (above median) | % of N (above median/overall) |
|---|---|---|---|---|---|
| ≥90 | Online | 91.25 | 4 | 3 | 75 |
| | Traditional | 91.00 | 4 | 2 | 50 |
| 80–89 | Online | 84.52 | 23 | 11 | 48 |
| | Traditional | 84.00 | 21 | 13 | 62 |
| 70–79 | Online | 75.33 | 6 | 4 | 67 |
| | Traditional | 73.00 | 6 | 3 | 50 |
| 60–69 | Online | 67.00 | 5 | 0 | 0 |
| | Traditional | 61.50 | 2 | 1 | 50 |
| ≤60 | Online | – | – | – | – |
| | Traditional | 44.00 | 3 | 0 | 0 |

guidance. This is an advantage that the traditional teaching mode does not have. Similar to Lu's results, the academically lower (or higher) performing students in the online course did not show any difference in their scholastic aptitude compared to those in the traditional course. By comparing the final exam average scores of overall and of the academically lower and higher-performing students between the online and traditional groups, no significant differences were observed. In contrast, Lu's results indicated that the lower performing students showed a significantly poorer test performance in the online teaching mode. Our equal online learning effectiveness for academically lower and higher-performing students might be the result of the optimized online teaching mode with smart interactive tools, which solved the problems available with the previous online teaching mode about the lack of synchronous interaction in class.

The smart interactive tools used in our online class have various functions. Class quiz designed from the main points of each section is the most popular one among the interactive functions. Random roll call makes students not dare to distract in class in case they do not know how to answer the questions. Real-time barrage allows all students to answer the question together. The "do not understand" button is suitable for shy students who do not like to communicate with the teacher through real-time interaction. By clicking the "do not understand" button at the bottom of the slide, the teacher will see the number of students who do not understand the content of this slide and give a more detailed explanation. As teachers and students are not in the same space, real-time interaction is difficult in previous online teaching mode. Teachers are unable to know whether the students understand the teaching content through students' facial expressions and question feedback. Through the above-mentioned smart interactive functions, the students may ask the teacher for help in time. The qualitative research will be designed in the future to link each smart interactive tool to different type of interactions and the corresponding instructional strategies to analyze student satisfaction in depth.

After class, teachers can view the students' interaction data, including the accuracy rate of class quiz answers, the students who posted the question barrage, and who did not understand a certain slide of PowerPoint. Meanwhile, some other data obtained from the smart interactive tools, such as the time taken by students to read the preview and review materials, and the accuracy rate of quiz answers, the teacher could evaluate whether the students complete the learning tasks well, whether they fully understand the teaching content of the course, etc. The teachers will communicate with the student who did not participate in the interaction or did not complete the preview and review tasks, through WeChat. After this kind of in-depth communication, students would know that the teacher is paying attention to them, so they will naturally keep attention to learning online courses. After the teachers communicated with several students who did not actively participate in interaction or did not complete the homework, the student's enthusiasm in class and the completion of homework were improved. Through data analysis after class, the teachers would also in-depth communicate with those students whose learning ability is found to be poor and help them ameliorate their learning strategy and solve their problems.

Comparing to the student number and average score of different band scores, no one failed in the online course, but there were three academically lower-performing students who failed in the traditional course. The number and average score of online students in the band score from 60 to 69 were higher than those of traditional course. These results suggested that using the online smart interactive tools, the teachers can easily find those students with lower learning motivation, and provide personalized guidance in time, so that these students could finally pass the exam smoothly. However, traditional teaching cannot grasp the learning situation of each student, resulting in the students with learning difficulties who cannot be taken care of by the teacher in class could not pass the exam. In the band score above 70, no significant differences were observed in the average score and student number between the two teaching modes. The final exam average score of overall and of the academically lower and higher-performing students between the two teaching modes showed no significant differences as well, which indicated online teaching could achieve the same teaching effect as traditional face-to-face teaching by improving instructional design and increasing teacher-student interaction. To increase students' enthusiasm for online learning, we evaluate the interactions in class *via* formative scores, including attendance rate, the accuracy rate of quiz answers, class participation, etc., and count the formative score in the final score. Since the final score of last year's traditional course did not include the formative score, we could not compare this part. This study was implemented in an elective course, which might have a potential sampling bias. However, the comparisons were performed between the students from traditional and online course who voluntarily chose this course and have the similar motivation to follow this course. The above results showed the optimized online course with smart interactive tools could improve the learning effectiveness for the academically lower-performing students in this course. Furthermore, we will collect more evidence from other courses and conduct comparative analysis.

There are also some drawbacks to smart interactive tools. For example, the functions of Rain Classroom need to be further developed in the future, such as real-time audio or video interaction. The new version Rain classroom 4.4 updated in 2021 already allow teachers and students to access microphones and cameras at the same time with real-time online interactive functions so that there is no need to nest other interaction tools like Tencent Meeting simultaneously. In the spring semester of 2022, we plan to adopt a blended teaching mode of this course. Based on the face-to-face synchronous interaction, the smart interactive tools will be used online to enhance learner-content interaction and instructor-learner interaction, optimize the teaching strategy in time *via* the feedback from data analysis, and increase students' learning motivation and effectiveness.

In summary, by using the optimized online teaching mode with smart interactive tools in higher education, the interaction can be perfectly realized, which ensures the online learning effectiveness of academically lower-performing students. Meanwhile, teachers can also know the learning status in which each student is and perform personalized guidance accordingly with the data analysis function of smart interactive tools to increase students' learning motivation. The promotion of online teaching with smart interactive tools in higher education will help optimize the teaching ecosystem gradually, cultivate students' self-study ability, realize personalized teaching, and improve the exam passing rate in the era of big data.

## 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

Written informed consent was obtained from the individual(s) for the publication of any potentially identifiable images or data included in this article.

## AUTHOR CONTRIBUTIONS

PW, TM, L-BL, and Y-XX designed and prepared the materials. PW, CS, and PA performed the data collection and analysis. PW wrote the first draft of the manuscript. All authors contributed to the article and approved the submitted version.

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# Basic Skills in Higher Education: An Analysis of Attributed Importance

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Today, the skills-based approach is increasingly in demand by companies due, in large part, to the fact that it favors the management of human resources by focusing on individual capabilities; which, finally, improves the job profile of a company. As a result, choosing the right candidates has become increasingly selective. Universities, therefore, need to teach skills to improve the incorporation of graduates into the workplace making it as successful as possible. For this reason, it is of special relevance to know if college students consider that the acquisition of skills is key for their incorporation into the workplace. The main objective of this study was to analyze and compare the importance assigned to the acquisition of basic skills in the university education of 694 students studying four different bachelor degrees: pedagogy, early childhood education, primary education, and psychology. For this purpose, a Likert-type questionnaire on basic skills was distributed with four possible options and the following five dimensions that grouped basic skills: organizational and planning capacity; access to information sources; analysis and synthesis of texts, situations, and people; teamwork; and problem solving. The results show that as a whole all students across different bachelor degrees gave a high score to the acquisition of basic skills, with early childhood education students giving it greater importance compared to the students from other disciplines and, more specifically, differences were observed in some dimensions depending on the bachelor degree that they have started.

**Keywords: self-perceptions, basic skills, higher education, college students, attributed importance, teaching method**

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## INTRODUCTION

In recent decades, a continuous and profound change has been taking place in social and labor reality, necessitating universities to regularly adapt to the new professional needs that the labor market demands from future graduates (Martínez-Clares and González-Morga, 2018; Pineda-Herrero et al., 2018; Rodríguez-Gómez et al., 2018). In fact, it is well known that the prestige of universities depends on the success of graduates, and this is one of the pillars of the triple helix, along with industry and government (Etzkowitz and Leydesdorff, 2000).

With the old university model, educational institutions sought to prepare professionals without paying much attention to the labor insertion of these people once they had completed their university studies, and without concern about whether they would be able to acquire a job associated with their qualification. However, in Spain, BOE (1983), resulted in the implementation of a new training model based on skills, and university education has undergone an important transformation which has generated a new university model in which a great interest can now be seen in all aspects concerning the insertion in the job market of professionals trained at universities (Eslava-Suanes et al., 2018; García-Blanco and Cárdenas, 2018; Gutiérrez et al., 2019; Baquero and Ruesga, 2020). According to Torres and Vidal (2015), "To talk about employability is to talk about aptitudes and attitudes, about a vital syllabus and about good personal qualities; that is, better or worse possibilities of access and adaptation to the job world" (p. 65).

If not addressed, the expense that this education entails would represent a relevant social and economic "loss," since the money and resources spent on training these students would not be economically or socially profitable, nor would there be any benefit from the time and resources used (Galcerán, 2010, p. 94).

One of the key aspects in this transformation of the teaching–learning processes in European universities, and specifically Spanish ones, is the syllabus design based on learning by skills (Pozo and Bretones, 2015; Calderón et al., 2018). However, even though more than two decades have passed since the implementation of a syllabus based on the acquisition of skills in European universities, the member states point out a multitude of difficulties in implementing this methodology (Ramírez-García, 2016).

In a more general sense, the term "skills" refers to the norms, techniques, procedures, attitudes, and abilities that future graduates acquire as they go through university, to perform their professional functions appropriately (Biccoca, 2018; Martínez-Clares and González-Morga, 2019; Gargallo et al., 2020). Therefore, the emphasis on skills "would mark the importance given to the student's own learning and to the development of their ability to interact creatively with the environment" (Galcerán, 2010, p. 104).

In the Tuning Educational Structures in Europe Project, an exhaustive distinction of skills or competences is presented: "[. . .] skills can be divided into skills related to a field of expertise (specific to a field of study), and generic skills (common for different courses)" (Tuning Project, 2007, p. 37). The generic or basic skills identify shared attributes which could be general to any degree, such as the capacity to learn, decision making capacity, project design and management skills, which are developed in all study programs. On the other hand, subject-specific skills refer to theoretical, practical and experimental skills and knowledge for a specific area or study program. Therefore, it can be said that transversal, generic, or basic skills refer to the elements common to any degree, while specific skills refer to the elements of each degree. In Spain, Ministry of Education and Science (2007) by which the organization of official university education was established, reference was already made to the establishment of two types of skills in college education with the purpose that the knowledge, skills, and abilities acquired in universities can be adequately adapted to the demands of the job market.

Nevertheless, there is still a significant gap between the knowledge, skills, and abilities that students acquire in their college studies and the required demands of the job market (Planas, 2010; Wild and Schulze-Heuling, 2020). Following this line, some authors point to the existence of a clear mismatch between the capacities and abilities learned by students in universities and the professional capacities required in the labor market for a successful performance of the tasks and functions in different jobs (Martínez-Clares and González-Morga, 2018; Aranda et al., 2021). This mismatch is currently presented as a great problem in the higher education system and, therefore, it is recommended that all the agents that make up the educational system reach consensus on the practical training of students (Pujol-Jover et al., 2015; Cabezas-González et al., 2017).

It is recommended that, at all levels in educational institutions, the development and acquisition of skills is promoted, and especially of transversal, generic, or basic skills, which are those that really provide the student body with great flexibility in different work functions and the ability to adapt to different jobs (Méndez et al., 2015; Rodríguez-Gómez, 2018). In this sense, there are various works that are relevant to the role of praxis by teaching staff, since they consider that professors are really those who are trained to improve and innovate the learning of college students (Biesta, 2015; La Rosa, 2015; Méndez et al., 2015).

Less importance has been given to the figure of the student body. However, college students must be motivated to acquire skills. Previous research shows that, even in stages prior to university, student interest is a key factor for adequate academic training (Rodríguez et al., 2020). All of this, together with the increasingly active role of the student body in their training (Aranda et al., 2015; López-Núñez et al., 2019), renders the attitude and motivation of students in university education with regard to skills as relevant (Centeno and Cubo, 2013).

Previous research analyses the perception of students in the acquisition of competences in the different university degrees (Gimeno-Santos and Martín-Cabello, 2007; Gómez-Puertas et al., 2014; Belmonte-Almagro et al., 2019). It is worth highlighting the work carried out by Belmonte-Almagro et al. (2019), where it is shown how, at a global level, students value the acquisition of competences in universities acceptably. Following this same line of research, in the study by Gimeno-Santos and Martín-Cabello (2007), a high score was also obtained in the importance attributed to the acquisition of competences in the Degree of Psychology by the students. More specifically, in the work of Gómez-Puertas et al. (2014), it is concluded that the students of the Degree in Journalism manifest a positive assessment in the acquisition of skills related to the capacity for critical and reflective analysis on their own actions.

The fact that students value the acquisition of competences very positively is of special relevance, since, if university students do not value training through the acquisition of competences, they will not be motivated and, therefore, they will not be adequately trained professionally. It is important that students value skills favorably, since they are an active part of the teaching-learning process.

Therefore, the general objective of this research was to analyze the importance assigned to the acquisition of generic or basic skills by college students in 1st-year study of different degrees and to identify if there are differences in said assessment depending on the degree under study. This research attempted to answer the following questions: What assessment do students give to the acquisition of skills in higher education when they begin their undergraduate studies? Are there differences among the students regarding the importance attributed to the acquisition of skills depending on the degree they are studying?

## MATERIALS AND METHODS

### Participants

The sample was selected through a non-probabilistic and intentional sampling, based on accessibility criteria. This sample consisted of 694 students belonging to four disciplines in the faculties of Educational Sciences and Psychology at the Universities of Malaga, Granada, and Seville, specifically in pedagogy, early childhood education, primary education, and psychology (see **Table 1**). Of the total participants, 6.9% were men and 93.1% were women. The difference in ratio between male and female students is due to the fact that the degrees considered in this research are biased by gender. As is well known, the educational trajectories between women and men differ and in some subjects one gender prevails over another. Specifically, in the degrees considered in this study, the female gender predominates over males.

### Instruments

To assess the importance given to basic skills, a questionnaire consisting of 52 items was used, adapted from Gimeno-Santos and Martín-Cabello (2007). The response format used was a Likert 4-point scale with the following options (1 = not at all, 2 = little, 3 = fairly, and 4 = a lot).

The items were grouped into five dimensions, each related to the basic skills expected of college students: Organizational and planning capacity (OP; e.g., "Have the necessary information to be able to carry out an academic work"); access to information sources (AF; e.g., "Knowing how to search in a library or newspaper archive for all the information you need"); analysis and synthesis of texts, situations, and people (AT; e.g., "Be able to synthesize a text"); teamwork (TE; e.g., "Actively listen to people"); and problem solving (RP; e.g., "Ability to understand that the same situation can have different ways of solution").

The reliability of the questionnaire was calculated using Cronbach's Alpha test based on the analysis of the responses of the 694 male and female students surveyed, and shows a high index of internal consistency ($\alpha = 0.895$). For each scale, the reliability values were also adequate; specifically, for organizational and planning capacity, the $\alpha$ value was 0.716; access to information sources, 0.849; analysis and synthesis of texts, situations, and people, 0.835; teamwork was 0.725; and finally, in the problem-solving dimension, the $\alpha$ value was 0.800.

**TABLE 1 |** Distribution of students by bachelor degree.

| Degree | *n* | Percentage |
|---|---|---|
| Pedagogy | 133 | 19.2% |
| Early childhood education | 183 | 26.3% |
| Primary education | 279 | 40.2% |
| Psychology | 99 | 14.3% |
| Total | 694 | 100% |

### Procedure

All data were collected during the second term of the academic year 2018–2019 and 2019–2020 at the Universities of Málaga, Granada, and Sevilla. **Table 2** shows the distribution of students by universities and degrees.

At the beginning of each data collection session, a brief explanation of the test was given to the participants, urging them to answer the question "if you were a professional of... do you regard it as important." In addition, informed consent was requested and provided, and the confidential nature of the information collected was communicated.

### Data Analysis

The methodology used in this research was quantitative. First, a descriptive analysis of the variables among the degree courses and the different dimensions contemplated in the questionnaire was conducted. Subsequently, a *t*-test analysis to assess gender differences, and an analysis of variance (ANOVA) test was run to determine if there were differences in the importance given to skills based on the course taken. Then, in order to verify the differences between the groups, Tukey's *post-hoc* test (multiple comparisons) was performed. Finally, to estimate the effect size, Cohen's d for *t*-test and partial eta square ($\eta^2{}_p$) for ANOVA was applied, with the following considerations in terms of value: for Cohen's d values of 0.1 represents a small effect size, 0.3 represents a medium effect size and 0.5 represents a large effect size (Field et al., 2012); for partial eta square: 0.0099 = small, 0.0588 = medium, and 0.1379 = large (Richardson, 2011).

## RESULTS

First, the means and standard deviations by dimension were analyzed, and the findings were that students, in general, attribute a high or very high average score to the importance of basic skills, with values exceeding three points out of four (see **Figure 1**). Therefore, it can be said that the skills perceived by students as more important or necessary for their professional development would be those framed in dimension 1 (organizational and planning capacity) followed by dimension 5 (problem solving), while those perceived as the least important

**TABLE 2 |** Distribution of students by universities and degrees.

| University | Degree | *n* |
|---|---|---|
| University of Málaga | Pedagogy | 133 |
| | Early childhood education | 183 |
| | Primary education | 54 |
| | Psychology | 55 |
| University of Granada | Primary education | 117 |
| | Psychology | 44 |
| University of Sevilla | Primary education | 108 |
| Total | | 694 |

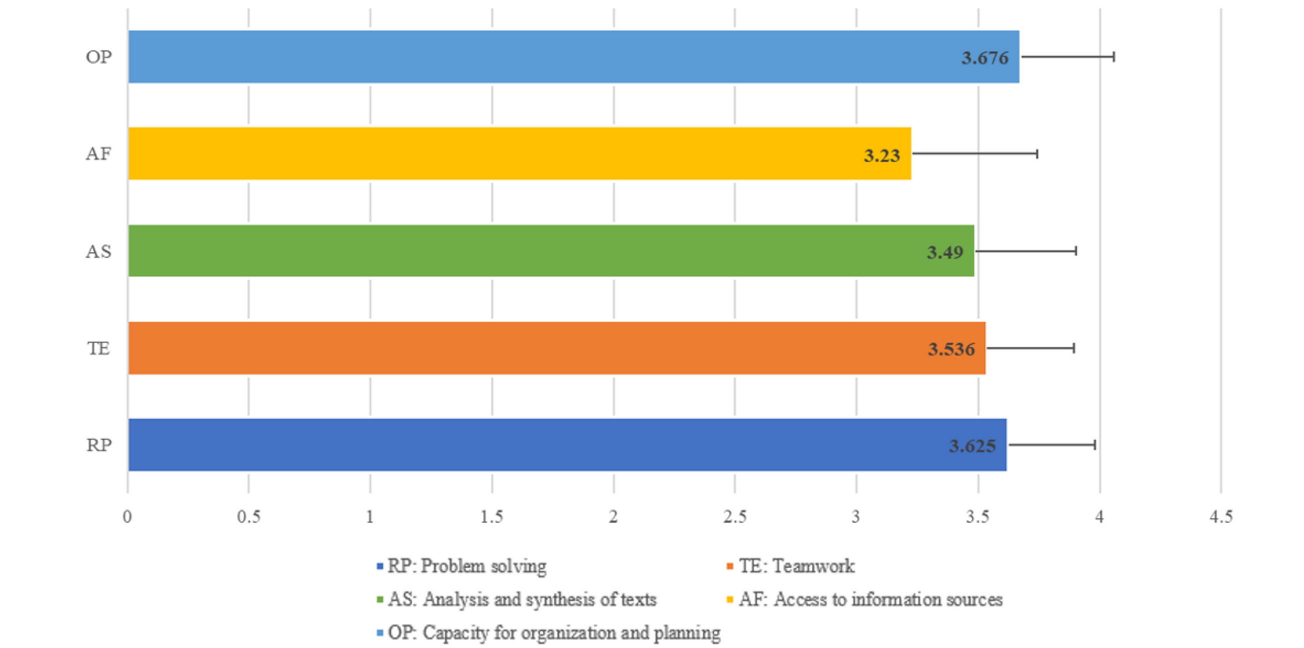


**FIGURE 1 |** Mean scores of basics skills.

for their professional career would be in dimension 2 (access to information sources).

Regarding gender, significant differences were observed between men and women in the importance given to Capacity for organization and planning ($t_{(687)} = -3.675$, $p < 0.001$, $d = 0.374$) and Problem solving ($t_{(687)} = -3.476$, $p = 0.001$, $d = 0.354$). In both cases, women scored higher than men in the importance given to these basic skills. In the case of Capacity for organization and planning, women scored on average 3.701 (SD = 0.375) and men 3.55 (SD = 0.385), for Problem solving women's scores were on average 3.647 (SD = 0.350) and for men 3.521 (SD = 0.359).

Subsequently, an ANOVA was carried out to explore whether there were differences in the importance given to basic skills according to university degree (**Table 3**). The results in all the analyses were significant, so the degree taken influences the importance attributed to the skills. The effect sizes were in all cases medium, with the lowest being for teamwork (0.039) and the highest for organization and planning capacity (0.070) and problem solving (0.066).

To determine the differences between groups, the Tukey *post-hoc* contrast test was performed. The mean scores for each dimension by bachelor degree are shown in **Table 3**.

With reference to the first dimension analyzed (capacity for organization and planning), significant differences are observed between the importance given to this dimension by the early childhood education degree students, whose score is significantly higher than students in the pedagogy degree ($p < 0.001$; 95% CI = [0.1446, 0.3603]), primary education degree ($p < 0.001$; 95% CI = 0.1333, 0.3149]) and psychology degree ($p < 0.001$; 95% CI = [0.0696, 0.2980]).

An analysis of the second dimension (access to information sources), shows that primary education degree students score significantly lower in this dimension compared to students in pedagogy ($p < 0.001$; 95% CI = [−0.3431, −0.0814]), early childhood education ($p < 0.001$; 95% CI = [−0.3668, −0.1302]), and psychology ($p < 0.01$; 95% CI = [−0.3246, −0.0452]) degrees.

In the case of the third dimension (analysis and synthesis of texts, situations, and people), the Tukey test revealed differences in the scores of studying early childhood education degree compared to primary education ($p < 0.001$; 95% CI = [0.1133, 0.3088]) and psychology ($p < 0.05$; 95% CI = [0.0185, 0.2645]) degrees, with early childhood education degree students scoring the highest in this dimension. In addition, students of the degree in pedagogy scored higher than those in primary education degree ($p < 0.05$; 95% CI = [0.129, 0.2291]).

Referring to the analyses carried out on the fourth dimension (teamwork), statistically significant differences are once again observed between students of the pedagogy and early childhood education degrees ($p < 0.05$; 95% CI = [−0.2104, −0.0031]), and between the early childhood education degree students and those taking the primary education ($p < 0.001$; 95% CI = [0.0855, 0.2599]) and psychology degrees ($p < 0.01$; 95% CI = [0.0456, 0.2651]), respectively. In all cases, the group of early childhood education degree students attributed greater importance to the teamwork dimension.

Finally, if we consider dimension 5 (problem solving), again the students of the early childhood education degree obtain a significantly higher score when compared with the students of the pedagogy ($p < 0.01$; 95% CI = [0.0794, 0.2815]), primary education ($p < 0.001$; 95% CI = [0.1211, 0.2912]) or psychology ($p < 0.001$; 95% CI = [0.1226, 0.3366]) degrees.

In short, there are statistically significant differences between all the degrees participating in this research with slight nuances although, after the analyses, the students in early childhood

**TABLE 3 |** One-way Analysis of Variance (ANOVA).

| Basic skill | Degree | *M* (SD) | *F* | *p* | $\eta^2_p$ |
|---|---|---|---|---|---|
| OP | Pedagogy | 3.59 (0.45) | 17.186 | 0.000 | 0.070 |
| | Early childhood education | 3.84 (0.21) | | | |
| | Primary education | 3.61 (0.40) | | | |
| | Psychology | 3.65 (0.37) | | | |
| AF | Pedagogy | 3.28 (0.46) | 12.650 | 0.000 | 0.052 |
| | Early childhood education | 3.32 (0.42) | | | |
| | Primary education | 3.07 (0.50) | | | |
| | Psychology | 3.25 (0.51) | | | |
| AT | Pedagogy | 3.49 (0.41) | 10.105 | 0.000 | 0.042 |
| | Early childhood education | 3.58 (0.32) | | | |
| | Primary education | 3.37 (0.40) | | | |
| | Psychology | 3.44 (0.45) | | | |
| TE | Pedagogy | 3.54 (0.38) | 9.334 | 0.000 | 0.039 |
| | Early childhood education | 3.64 (0.28) | | | |
| | Primary education | 3.47 (0.35) | | | |
| | Psychology | 3.49 (0.41) | | | |
| RP | Pedagogy | 3.59 (0.40) | 16.251 | 0.000 | 0.066 |
| | Early childhood education | 3.77 (0.24) | | | |
| | Primary education | 3.56 (0.35) | | | |
| | Psychology | 3.54 (0.39) | | | |

*OP: capacity for organization and planning; AF: access to information sources; AT: analysis and synthesis of texts, situations, and people; TE: teamwork; RP: problem solving.*

education degree stand out as the group that placed the highest values on the five dimensions measured by the questionnaire, as basic and necessary skills required by an educational professional.

## DISCUSSION

The objective of this paper was to evaluate the importance assigned to the acquisition of skills by 1st-year college students of different degrees and to identify if there are differences in such assessment depending on the type of studies, since different studies (Rabanal et al., 2020; Sarceda and Barreira, 2021) show that academic training in competencies is one of the key points in the face of labor insertion, a comprehensive training that considers both personal and social motivations so highly valued in the world of work.

Overall, the results obtained show high scores in the importance attributed to basic skills by the four degrees considered in this research. Although a positive assessment by the students of the different groups is observed, according to our results, on the one hand, statistically significant differences were observed between the different study groups (degrees) and by gender, although with a moderate effect size. The sample of this work had a greater number of female participants, something common in education and psychology degrees in Spain. The two skills that have shown significant differences are usually associated with males, since there are gender stereotypes in relation to educational skills such as problem solving (Zhu, 2007). It is possible that women, considering that they possess these skills to a lesser extent, attach more importance to their development than men.

On the other hand, we note that the early childhood education students placed highest value on the five basic skills included in this research compared to the three remaining groups (pedagogy, primary education, and psychology). All these differences observed between the different degrees can be explained, at least in part, by the characteristics of each degree and the target audience they are targeting.

Following this line of thought, the study undertaken by Meroño et al. (2018) indicates that, in addition to the perception of teachers and educational agents, it is necessary to be aware of the perception of students in their own skills learning since their opinion is essential to improve the learning processes in terms of skills. This is especially important in students with special educational needs, since the development of their abilities and skills require specialized attention from teachers (Tanu and Kakkar, 2018; Kakkar, 2020).

This aspect arouses great interest, since the students' perceptions of their own knowledge, the importance they give to the teaching methodology, and the motivation toward their teaching process is key to achieving greater involvement in their own training (Castells et al., 2015; Martínez-Clares and González-Morga, 2018). In fact, one of the great challenges of the university is that the students become the main figure in their entire college learning process by actively participating in their training (Silva, 2017; Pegalajar, 2020).

The importance of this research has to do with a recently coined term, "academic commitment," which could be defined as a concept that includes a wide variety of student behaviors and academic practices such as time spent on academic tasks, adaptability, social and academic integration, and teaching methodology (Kahu and Nelson, 2018). Basically, this concept refers to the importance of the opinions and well-being of the students in every way in order to achieve adequate academic preparation that helps them face the important changes that are taking place in society and specifically the demands of the job market (Martínez-Clares and González-Lorente, 2018).

Therefore, it becomes necessary to remove one of the major drawbacks to planning and developing teaching–learning methodologies taught in universities such as the importance that has always been ascribed to the theoretical aspect of the subjects compared to the practical function. Several authors have pointed out that, in general, at university much importance is given to the theoretical content of subjects, while the job market demands that future workers "know how to do it" (Alonso et al., 2009; Jackson, 2012; Torres and Vidal, 2015). This explains why some authors demand greater coordination between university training and the demands of the job market (Cabrera et al., 2016).

Similarly, Ellwanger and Andreucci (2017) refer to the need for college professor teachers to undertake comprehensive training of students, so that in addition to theoretical knowledge, students develop practical and motivational skills. Regarding the development of practical skills, an important issue must be kept in mind, that is, to efficiently implement skills in the current academic curriculum design in universities (Calderón et al., 2018; Glaesser, 2019; Ahmed and Khairy, 2020). This inevitably leads us to reflect on the training of professors in higher education to apply teaching–learning strategies based on skills, particularly basic skills. At this point, several problems in universities can be highlighted, the main issue being that despite working in a higher-level institution the vast majority of university teaching staff have not had specific training outside of the skills of their field of expertise, let alone received pedagogical training to carry out their professional careers, unlike the other educational levels. This is a paradox since they are required to teach skills without having previously received any training in this regard. Faced with this professional challenge, the pedagogical training of professors is key to professional success (Más-Torello, 2011).

Another problem faced by professors is that they generally have very high ratios in the number of male and female students, and this renders a more personalized teaching among professor-students that favors the acquisition of skills impossible. Furthermore, the time availability of college teaching staff must be considered since, very often, professors do not have the available time to enable them to propose subjects, including the skills to be developed and the way to assess them (Villarroel and Bruna, 2014). For this reason, it is essential that teachers participate in and grant special dedication to the inclusion of basic skills in their methodological strategies (Villarroel and Bruna, 2014). It is essential for professors to reflect on and review these methodological strategies when considering the perception and importance placed by students on the acquisition of transversal, generic, or basic skills in their college studies (Rodríguez-Gómez et al., 2018), as it has been possible to verify after the results of this research, since the 5 groups of students have a great motivation toward learning by competences.

Based on the above, we can affirm that, if students consider the inclusion of skills in the syllabus to be important, they will show a predisposition to be part of their skills learning and, with this, progress can be made in two basic aspects in the higher educational context. One of these aspects would be the progressive increase in the participation of students in their own college education, thus achieving a more autonomous and active role (López-Núñez et al., 2019); and the other would be motivation in teaching methodologies, which is key to performance and would lead to academic success.

Within the inclusion of skills in the syllabus of the different degrees of our universities, the so-called generic, transversal, or basic skills are of special interest since, if the development of these most basic abilities and skills is encouraged, students will learn to adapt more satisfactorily in the social sphere and, more specifically, in the workplace in increasingly changing contexts. In this sense, Brussels has proposed the preparation of students for their adequate adaptation to the increasingly profound changes in the job market, training citizens of increasingly digital and global societies (Consejo de la Unión Europea, 2018).

This study has some limitations: Although the sample is large, the data was collected at a single point in time. In the future, longitudinal studies should be added to establish the importance given to skills changes as students advance through the years. On the other hand, it would be useful to know the importance ascribed to these skills by those studying college degrees in other fields and to compare the results.

## CONCLUSION

In conclusion, universities must prepare both professors and their students for the new challenges of the 21st century. It is necessary for professors to train in skills to be able to teach them. In addition, it is important to take into account the attitude and perception of all educational agents, and more especially the perception of students as the main educational agent in the university context. The need to identify which skills are demanded by the job market to adjust both the basic and specific skills of students in an academic context to the labor demands must be considered. For this reason, it is also essential to pay attention to the companies that employ graduates, since they provide hints on the skills currently being demanded in a changing society in which employment has to gradually transform and reinvent itself on a daily basis. In this way, the educational quality will increase, and the professional success of the students will be more likely.

## DATA AVAILABILITY STATEMENT

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

## AUTHOR CONTRIBUTIONS

LA designed the study, supervised the data collection, and wrote the manuscript. EM-R carried out the statistical analysis and wrote the manuscript. LR supervised the data collection and assisted with writing the article and edited the manuscript. All authors contributed to the article and approved the submitted version.

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# The Teaching Brain: Beyond the Science of Teaching and Educational Neuroscience

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## INTRODUCING THE TEACHING BRAIN

The field of neurodidactics studies has amplified knowledge about learning processes, focusing on the learning subject and the implications for teaching-learning brain (Goswami, 2004; Strauss, 2005; Battro, 2007, 2010; Fischer, 2009; Fischer and Daniel, 2009; Geake, 2009; Immordino-Yang, 2016; Willingham, 2017; Tibke, 2019).

The data and research supported by neuroscience that invest at different levels the theories and practices of education are not new, by way of example: Iran-Nejad et al. (1992) stressed the value of a biological perspective in education; Jensen (2005) connects the role of different cognitive processes (such as emotions, attention, motivation, and rewards) to learning processes (e.g., he discusses why the stress response impedes learning), Willingham and Llyod (2007) describe four techniques to integrate neuroscientific data into the psychological theory of educational constructs (such as reading), and Schwartz (2015) presented the evolution of research at the intersection between neuroscience and education.

The rapidity with which attention to educational neuroscience and the relationship between education and the brain has evolved, led to the development of neuromyths (Geake, 2009; Sousa, 2011). Neuromyths have been defined as "misconceptions generated by a misunderstanding, a misreading or a misquoting of facts scientifically established (by brain research) to make a case for use of brain research in education and other contexts" (OECD, 2002, p. 69). To mention a few, they include the polarization of brain hemisphere specialization and its relationship to learning, the misconception that brain plasticity is relative only to specific critical events, the idea that learning improves or is facilitated under conditions of higher synapses (Goswami, 2004; Santoianni, 2019), the use of only "10% of our brain", the acquisition of information about specific preferred learning styles (Howard-Jones, 2014). To establish a correct dialogue between neuroscience and education, these misconceptions should be explored, as done by recent studies (e.g., Hermida et al., 2016), and addressed in practice with the appropriate information, neuroscience courses, or training.

Furthermore, the idea that neuroscience can inform and potentially influence education raises controversy and open debate (Ansari et al., 2012). Meirieu (2018) argues that the neuroscientific approach would only be able to visualize the existence of a human being through brain activity and the image of the mind, but not the content that forms and sustains thought and generates knowledge. One of the major criticisms often concerns the artificiality of neuroscientific experiments that cannot be easily applied to real educational contexts, neuroscientific knowledge is far removed from classroom interactions, some facets of neuroscience are not relevant to some facets of classroom learning (Bruer, 1997; Colvin, 2016).

To overcome this limitation, cognitive applied neuroscience research started to apply neuroscientific tools in highly ecological contexts, such as the classrooms (Brockington et al., 2018). Also, in the two-person (teacher-student) educational neuroscience, the relatively newborn hyperscanning paradigm in neuroscience, that involves capturing the brain activity of two or more participants engaged in interactive activities at the same time (Babiloni and Astolfi, 2014; Balconi and Vanutelli, 2017; Crivelli and Balconi, 2017) may allow researchers to grasp the relation between the teacher and the learner (or even the class group) (Dikker et al., 2017; Pan et al., 2020). Hyperscanning can be defined as a method that allows for the performance of human behavioral experiments in which participants can interact with each other while brain neuroimaging data is acquired in synchrony with the behavioral interactions (Montague et al., 2002).

Accordingly, although the provocation of the French philosopher (i.e., Meirieu), still feeds widespread neuroscepticism (see for example the Editorial, 2005; Bowers, 2016; Krammer et al., 2021), it finds some opposite positions and evidence in several recent studies that support the blending of neuroscience and education as an engine of knowledge (Thomas, 2019; Davidesco, 2020; Davidesco et al., 2021). According to this view, the knowledge of how the brain works and its anatomy could contribute to (i) the understanding of teaching-learning processes, and (ii) the identification of learning environments oriented to promote and support neuroplasticity and that could be facilitators of the learning process. Several studies link brain plasticity with the ability to learn, explaining how this is closely dependent on changes related to the architecture and chemistry of our brains (Caine and Caine, 2006).

Despite this multiplicity and the prevailing focus on the brain of the learner and learning as a cognitive function and neural processes, relatively few studies to date have specifically addressed a deeper understanding of the teacher's perspective according to the neuroscientific approach of the Teaching Brain (TB) (Fischer and Rose, 1998; Battro, 2010). Some works have been conducted specifically in the field of cognitive neuroscience and experimental psychology on the topic of TB exploring the basis of cognitive processes supporting teaching practices (Pasquinelli et al., 2015; Calero et al., 2018; Corriveau et al., 2018), compared to imaging and traditional neuroscience that focuses on a traditional localization approach. However, we believe that a two-person neuroscientific approach such as that of hyperscanning can best grasp the nature of TB, converging information on brain localization, cognitive and emotional processes, and student-teacher interactional dynamics. TB is a concept that reflects the complex, dynamic, and context-dependent nature of the learning brain, in fact, teaching is an interaction between two entities: the teacher and the learner (Rodriguez, 2013).

The next section will present the neuroscientific research on the topic of the teacher's brain and its interconnections with the teaching-learning relationship and teaching practices. Finally, we discuss how novel paradigms of neuroscience might account for and deepen the role of TB in the teaching-learning process, which is conceived in an interactive dynamic.

## NEUROSCIENTIFIC STUDIES ON THE TB

### Empirical Studies Analyzed on the TB

Without claiming to be exhaustive, the following paragraphs will describe the studies that, in line with the new trends in cognitive neuroscience, aimed to apply the neuroscientific tools outside the laboratory, directly in the classroom, and which used the hyperscanning paradigm to grasp the interactive dynamic between teacher and student. Unlike the two recent essays by Davidesco (2020), Davidesco et al. (2021), this contribution focuses on hyperscanning studies involving the figure of the teacher. The findings reported below might be particularly interesting for a better understanding of the TB perspective.

Research on the TB includes, in particular, those by Rodriguez (2013), Rodriguez and Solis (2013), and highlights how the teacher's brain is able to process student-centered information, forming a theory of student cognition that considers what the students are thinking and the knowledge they would be able to acquire and accumulate. Authors suggest teachers can, therefore, use this model to guide not only what the students are thinking and learning, but also what they would be capable of (Rodriguez, 2013). For instance, authors suggested that developing a theory of the student's mind, cognition, emotion, and memory allows teachers to tailor their demands to the student and invite them to learn what they deem impossible to learn. However, it must be clarified that the ability of the teacher to adjust its requests based on a representation of the student's learning brain has not been measured or verified experimentally.

In the two-person educational neuroscience framework, neuroscientific research by Holper et al. (2013) and Dikker et al. (2017) attempt to identify the cortical correlates involved in teacher-student interactions during the performance of a teaching model. The evidence reported by brain studies solicit relevant pedagogical variables in student-teacher interaction. Using the technique of functional Near-Infrared Spectroscopy (fNIRS), the research team of Holper et al. (2013) examined the hemodynamic brain correlates of teachers and students during a specific teaching activity based on Socratic dialogue and, concerning the TB, found that higher teacher-student brain synchrony positively correlates with dialogs in which the student transferred the learned knowledge. In a comparable way, but using the portable electroencephalogram (EEG) technique, Dikker et al. (2017) study was conducted attempting to neuroscientifically detect the synchronic relationship between teachers and students by recording, repeatedly over several days during a semester, the brain activity of a group of students and the teacher simultaneously while they were in the classroom. The results suggested that brain-to-brain synchrony is a sensitive marker that can predict both classroom engagement (students rated as more engaging watching videos and group discussions over listening to the teacher reading aloud or lecturing) and classroom social dynamics (in terms of social closeness ratings and social interactions) and that this relationship may be driven by shared attention within the group.

Also, Bevilacqua et al. (2019) adopted an EEG-hyperscanning paradigm and showed that social factors (e.g., perceived closeness) are reflected in the brain-to-brain synchrony of a student-teacher dyad and can predict cognitive outcomes such as students' academic performance. While Bevilacqua et al. (2019) found no link between student-to-teacher brain synchronization and students' performance on a knowledge test, two other research found the opposite (Cohen et al., 2018; Davidesco et al., 2019). For example, Davidesco et al. (2019) found that neural synchronization between students and between students and teachers predicted students' performance on a test given a week following a lecture.

To narrow the gap between experimental research conducted in the laboratory and the classroom environment, Brockington et al. (2018) initiated a series of fNIRS hyperscanning studies directly in the classroom to capture the brain activity and derived physiological phenomena of students and teachers in the typical realistic scenario of the educational relationship (i.e., in the first experiment the dyad was performing an interactive board game; in the second and third experiment, the students were attending a lecture). In their first study, authors revealed a close and positive correlation between a teacher's and a student's activation pattern [oxygenated hemoglobin (HbO) concentration changes] in the prefrontal cortex (PFC) during an educational interaction, which can be associated with a phase of monitoring of the student's actions by the teacher, which is crucial to verify the completion of an educational task. More interestingly, a positive correlation between the teacher's temporoparietal junction (TPJ) and the student's PFC changes in HbO was detected, demonstrating that the learning process is always a bidirectional transfer of knowledge, in which the student activates brain regions involved in high order cognition (e.g., PFC) and the teacher recruits parietal areas (e.g., TPJ) supporting social processes, like the capability of empathizing and perspective-taking. With the appropriate cautions, the neuroscientific correlations between the regions supporting mental processing in the teacher and higher cognition processes in the students highlighted by the group of Brazilian researchers (Brockington et al., 2018) suggested the neural-based bidirectional transfer of knowledge featuring this interaction and draw a synergy with the dynamic interaction models of the mind of the teacher and the learner (see Rodriguez and Fitzpatrick, 2014).

More recently, Pan et al. (2020) employed fNIRS hyperscanning to assess simultaneously the neural responses deriving from teacher-learner couples during two dynamic conceptual learning approaches (scaffolding vs. explanation approach). In this study, the scaffolding behaviors included asking guiding questions or providing hints, while the explanation approach comprised providing definitions or clarifications. The findings indicated that brain-to-brain coupling was linked with learning outcomes, and, more importantly, was driven by the teacher's scaffolding behaviors and not from an explanation approach. This evidence shows that, as a pedagogically relevant metric, the brain-to-brain coupling is associated with the naturalistic educational process during instructor-learner contact when engaged in a constructive dialog, but not when the teacher is providing clarifications or information.

Although taking place in situations as real as possible of teaching-learning, the research conducted by Dikker et al. (2017), Brockington et al. (2018), and that of Pan et al. (2020) have adopted very rigid protocols, reducing that naturalness present in the typical places of teaching and the educational relationship between students and teacher, an element that to date still constitutes one of the major limitations of the application of some neuroscientific techniques in educational contexts and that needs to be addressed with less invasive mobile devices. In addition, the exact positions in which the optodes are placed to create the fNIRS channels and montage are sometimes not specified in the studies considered above (e.g., first experiment by Brockington et al., 2018) and this can make the reproducibility of the study complex (Balconi and Molteni, 2016).

Furthermore, it is worth noting that these studies mainly include high-school or university students and therefore the results may be more directly relevant for this specific population group, however, we believe that they can also be taken into account for younger student populations.

Despite the instrumental constraints necessary to preserve the scientific-methodological rigor in the application of neuroscientific tools in an educational naturalistic context, it is necessary to conduct more neuroscientific studies to deepen the relationship between teacher and student and the TB perspective. With respect to what Davidesco (2020) pointed out, namely that these methods can integrate other types of measures (such as performance tests, self-reports, and think-loud interviews) and can deepen our understanding of the learning process, we add that they can be supportive also, in the analysis of the other perspective, that is of the teaching processes. The increase of research in this context would also favor the refinement of the application of wearable and wireless tools to ensure the naturalness of the interactive dyadic exchange.

## What Does the TB Suggest for Education and Teaching? The Added Value of Neuroscience

So far, there is a lack of appropriate tools to explore the TB, while a multiplicity of tools and methods has developed to explore the learning brain. The relationship of pupils and teachers in the study of teaching could become an immense source of knowledge and research on the development of the TB from the first school cycles. In this framework, the hyperscanning paradigm could be considered a potential way to overcome this gap. By allowing the simultaneous recording of the cerebral activity of the brain of the teacher-learner dyad, this paradigm will allow collecting information on student-centered and teacher-centered processing.

Moreover, the added value of neuroscience discipline is two-fold, since it consists not only in the capability of neuroscientific paradigms to provide information related to the implicit brain-and-body activity of the interactive dyad, but also in providing a range of mobile, wireless, non-invasive, and easy-to-use tools that can be exploited outside of the laboratory in real-life contexts (i.e., the classroom) with a high level of ecological validity.

The concept and research on the TB suggest that we can support teachers by valuing this approach to the study of teaching and education in general. It is not intended to outline a specific or rigid set of best practices, nor to offer a checklist that defines levels of good teaching: the underlying assumption, in fact, lies in noting that each individual teacher takes responsibility for his or her teaching. Instead, the TB framework can facilitate on the one hand the analysis of postures, neuronal markers of evidence of the teacher in the teaching activities and help to outline a path of identification, growth, and improvement (Rodriguez and Fitzpatrick, 2014), on the other hand, the results of neuroscientific evidence on the TB can allow reading how neural architectures infer behaviors and actions also directly related to teaching in real contexts.

## CONCLUSIONS

There are still few studies on this topic, which strictly anchor on the neuroscientific level of the TB: this is perhaps due to the difficulties in applying research in real-life contexts. However, research shows that some neuroscientific markers (such as brain-to-brain coupling that, for example, characterizes constructive engagement, but not information clarification; Pan et al., 2020) allow the identification of significant relationships between specific teaching methods and positive learning outcomes. This evidence must find a spillover on educational and teaching practices as well, also to modify the way of thinking about knowledge and learning processes, typical of the pedagogical perspective.

Also, two-person educational neuroscience can help to deepen the explicit and implicit levels of teaching and conceive the interactional dynamic from the teacher's view. To do so, some limitations should be overcome. Indeed, current neuroscientific studies could be divided into research that adopts very rigid protocols, reducing the naturalness present in typical teaching places and the educational relationship between students and teacher, or do not provide all the methodological details to allow replicability. Three main measures could be taken in the field of two-person educational neuroscience to address the weaknesses of current studies in this area and to increase the interpretation and application of the results. Firstly, less invasive mobile devices (wearable and wireless tools) should be adopted to ensure the naturalness of the interactive dyadic exchange between the learner and the teacher while collecting neuroscientific data. Secondly, neuroscientific studies should be designed in collaboration between neuroscientists and pedagogists to try to get as close as possible to the naturalness of the dynamics that occur in the classroom. Finally, while it is important to specify the methodological details and procedures used in these works, the evidence gathered from these studies should also be shared and translated in terms of applicability so that pedagogists and teachers can comprehend and implement it appropriately.

For educational contexts, this theme is relevant to build more functional and effective educational teaching methods and approaches, which are based on how the human brain works (both of the student and the teacher, in particular). While for psychology, the learning process is one of the basic themes of general psychology, and is relevant as a cognitive and emotional process, however, this has been studied mainly from the perspective of the student rather than of the teacher.

While using different methods and perspectives, the focus on the TB implies the possibility that knowledge from these studies can help teachers in their classroom work with students. The TB perspective also suggests that we are faced with dynamic processes of the brain on teaching, subject to continuous modifiability, and which therefore require continuous updating and in-depth analysis. It is a field of research still not much explored; with due attention to limits and potential, it can foster new instances and questions for reflection on educational research, on didactics, on the brain, and the interaction between teacher and student.

## AUTHOR CONTRIBUTIONS

GG and LA wrote the first draft and each section of the manuscript, contributed to the manuscript final writing and revision, read, and approved the submitted version. FC and MB contributed to the manuscript final writing and revision, read, and approved the submitted version. All authors contributed to the article and approved the submitted version.

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# Right Cortical Activation During Generation of Creative Insights: An Electroencephalographic Study of Coaching

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Coaching as a human development methodology has been demonstrating its results for more than four decades. Even so, the level of confusion about its essence and its lack of a definitive theoretical and methodological framework has caused its effectiveness to be questioned. Although studies on coaching with neuroimaging methodologies have been developed, there is no recent evidence about the brain changes in electroencephalographic (EEG) activity during a coaching session. The present research aims to make a comparison between EEG measurements of three different conditions, namely, rumination (R), directive (DC), and non-directive coaching (NDC), during the process of problem solving and goal achievement. Our hypothesis was that the use of the meta-competencies of NDC should induce a higher activation of brain mechanisms that facilitate the insight process, therefore causing an improvement in creative capacity. Results showed significant changes in alpha and theta frequencies in the right temporal region, and alpha, theta, and gamma in the right parietal region in the NDC condition compared to other experimental conditions. The correct use of the meta-competencies of NDC facilitates the rise of insight and the generation of creativity processes at the brain level. Thus, the application of the methodological framework of the NDC was related, in a specific way, to the creativity and the development of human knowledge.

**Keywords: creativity, insight, EEG, non-directive coaching, coaching**

## HIGHLIGHTS

- Meta-competencies of non-directive coaching increase the frequency of creative insights.
- Meta-competencies of non-directive coaching induce higher levels of creative ideas.
- Creative insights are associated with changes in alpha and theta frequencies in the right temporal region.
- Creative insights are associated with changes in alpha, theta, and gamma in the right parietal region.

## INTRODUCTION

Since the publication of the book "The Inner Game of Tennis" (Gallwey, 1979), coaching has undergone changes and transformations, leading us to a professional environment of confusion and ambiguity regarding its essence and theoretical and methodological framework (Ravier, 2016). Hence, the methodology of coaching has been frequently questioned, providing some confusion regarding its main methodological differences and identity with respect to others' care processes and therapies (Segers et al., 2011; Grant, 2015).

Coaching has emerged as a synthesis of various fields of knowledge, such as consulting, philosophy, the humanist movement, psychology, sports training, and systems theory (Ravier, 2005; Rock and Schwartz, 2006). This uncertain origin is one of the main obstacles to finding a clear and differentiated definition that can explain what coaching is. Although according to Rock and Schwartz (2006), different investigations explained how coaching works at brain level by neuroimaging techniques (Jack et al., 2013; Boyatzis and Jack, 2018). Despite this progress, none of them was neither based on non-directive coaching (hereinafter NDC) approach and its theoretical framework nor was employed with psychophysiological techniques for measuring brain activity during a coaching session. Electroencephalographic (EEG) techniques are widely used to provide an objective evaluation of brain correlates that occur during cognitive processes (e.g., deductive and inductive reasoning, generation of creative ideas, and metacognition) that could take place during a coaching session. In this sense, they would also allow us to compare the effectiveness of different coaching approaches to generate creative insights during problem solving and goal achievement. It is important to note that EEG can provide valuable data on the NDC approach's (i.e., where the coach does not make judgments or transfer knowledge or experiences about what is treated by the client) ability to generate insights compared to other conditions, such as the directive coaching (DC) approach (i.e., where the client receives clues and suggestions on how to solve their situation) or the ruminant state (Watkins, 2008) (i.e., in which the client thinks by himself repeatedly about the solution to the problem or goal).

From the perspective of non-directivity, understood as the non-transference of knowledge or experience, or the issuance of judgments by the coach, we can define coaching as a non-directive process: (a) where the coach is the person who accompanies the client through a professional client-centered relationship without interpretations or judgments; (b) it is a self-directed process, wherein the client is who determines the direction of the process; (c) which is established under conversations oriented to reflection, called dialogic; (d) it seeks to enhance and/or develop the tacit knowledge of individuals, in a creative way, where the client discovers or creates new knowledge in order to achieve their goals or solve their problems (Ravier, 2016). According to Ravier (2016), following the NDC approach and into the conversational field, we can distinguish three conversational meta-competencies: (a) paying phenomenological attention, which would mainly include observing and listening to the client's verbal, para-verbal, and non-verbal information; (b) mirroring faithfully, faithful return of what the client says and/or does in direct relation to the goal and coaching process; and (c) asking focused questions in order to enhance the client's capacity for association and reflection. Concerning the structural meta-competencies, two levels are distinguished: the first level is related with (1) the conversation structure represented by the GROW model (Whitmore, 2002; Alexander, 2005; Fine, 2010) within the conversation held in the coaching session. This model takes the form of a 4-phased model starting off with: (a) the goal design (G), (b) the exploration of reality (R), (c) the options generation (O), and finally (d) the design of actions (W). The second level is related with (2) the monitoring structure, marked by the model of the process scheme and monitoring of results obtained from actions carried out between sessions in order to achieve the overall coaching process goal.

One of the main characteristics of the coaching process mentioned in its definition is that it allows to enhance the creative capacity of the human being. The first studies on creativity began in the 1930s (e.g., Patrick, 1935, 1937, 1938), but it did not reach a consensus until, at least, 1953 (Stein, 1953). Focusing on the definition of creativity, Runco and Jaeger (2012) points out the need for a bipartite standard definition, in which creativity requires both originality and effectiveness. This means that the character of novelty and adaptation are the two differentiating elements within any definition of creativity. According to Fink and Benedek (2014), creativity implies the process of generating some original ideas to open problems, but as a cognitive process, considers the recovery of both existing knowledge in memory and the combination of various aspects of existing knowledge to convert them into new ideas (Paulus and Brown, 2007). Oliverio (2008) notes and emphasizes that the essential aspects of creativity are the ability to combine and mix in a new "capital" preexisting form and comparing it with knowledge that we already have at our disposal to create new associations.

However, Kounios and Beeman (2015) defined creativity as the ability to reinterpret something, decomposing it into its elements and recombining those elements in a surprising way to achieve a goal or solve a problem. Problem solving through divergent thinking is one of the most demanded skills in the professional and personal sphere due to how most of the challenges and problems that we face in our day-to-day life do not require logical thinking for their resolution. If they do not, they can only be solved through divergent thinking and through a generation of insights.

The concept of creativity cannot be dissociated from the phenomenon of insight (Duncker, 1945) since creativity is characterized by the solution of a problem not from a convergent reasoning or approach, but in an abrupt and spontaneous way. Insight can be defined as a transformative and non-incremental step during the solution of a problem that requires a successful restructuring or reformulation (Duncker, 1945). According to Sheth et al. (2009) we can identify the insight in two different ways. The first is to trust the feeling of "Aha!" of the subject once solved. The other way is to objectively classify a solution on the basis of cognitive processes. In order to identify insight from a cognitive process and not based on the individual subjectivity, it is important to focus on the following elements: a mental deadlock or impasse in which the subject is subjected to a situation in which he/she feels "stuck" and unable to continue (Fleck and Weisberg, 2004), and a restructuring or creation of a cognitive representation that was new or not obvious until then (Ohlsson, 2008). Regarding the psychophysiology of the cognitive process of insight, previous studies have identified local patterns of neural activity associated with "Aha!" experience based on electroencephalographic recording and event-related potential techniques (Jung-Beeman et al., 2004; Mai et al., 2004; Sheth et al., 2009). The cerebral cortex brain has the ability to generate different EEG frequency waves according to the mental activity that it is performing at that moment with an excellent temporal resolution. Therefore, EEG techniques offer us an opportunity to study the neurophysiological correlates that occur during a cognitive process (attention, learning, information retrieval) (Silva et al., 1999), or in this case, the efficiency of three different conditions [rumination (R), DC, and NDC] in the generation of insight during the emergence of creative solutions.

## AIM AND HYPOTHESIS

The general purpose of this study was to compare the effects of different conditions, namely, R, DC, and NDC, in the EEG activation of electrode sites related to the processes of generation of creative insights during problem solving and achievement of goals. Our specific objectives were as follows:

(1) To evaluate the functioning of the GROW model (goal, reality, options, and will) as a structural competence for the effective application of the NDC.
(2) To compare the capacity of the NDC to enhance the creativity and generation of insights compared to other conditions (rumination and directive coaching).
(3) To identify the NDC meta-competences that have a greater impact on the EEG activation of electrode sites related to the enhancement of creativity and the generation of insights.
(4) To measure the regional pattern of EEG wave frequencies associated with the generation of insights during NDC.

Brain regions of interest in other EEG studies have been directed to the analysis of the right cortical parietal and temporal activity (Kounios and Beeman, 2009; Sheth et al., 2009; Fink and Benedek, 2014) because they have shown significant activity changes when insights arise and creative cognitive processes are generated. Our hypothesis predicts that the use of NDC meta-competencies could induce the activation of right temporo-parietal regional patterns of EEG wave frequencies associated with creative cognitive processes of divergent thinking (insights) during problem solving and goal achievement.

## MATERIALS AND METHODS

### Participants

A sample of 16 voluntary participants (50% female) between 25 and 65 years old ($M$ = 42; $SD \pm 11.26$) were anonymously recruited through social media advertising to participate in the study. According to previous works, the sample size to consider is between 10 and 20 participants with 30–60 events per participant (Badcock et al., 2013, 2015; Larson and Carbine, 2017). We developed three tests per participant, and the average number of events (insights) per test was 45. Power analyses using the derived effect size estimates for EEG measures were calculated using Cohen's $d$ with $d$ = 0.8 and alpha = 0.05, indicating a medium effect. The age range has been determined based on the years in which a worker had a management position within an organization/company in our country (Spain). All the participants were informed about the aim of the study and that they could withdraw from the study at any point without further explanation. They were not rewarded by economic incentives for the involvement in the study.

In order to participate in the study, the following inclusion criteria were selected: (a) to have a management position within an organization/company regardless the number of people they have in charge, (b) no previous experience in individual or team coaching sessions, and (c) to have three goals or problems of a similar difficulty to solve at this time within their scope of management at work. The exclusion criteria were as follows: (a) The goals or problems should not have a direct emotional implication that might be susceptible to be approached from a therapeutic perspective, (b) The participants has not started to solve problems or achieve goals before attending the coaching session. All coaching-related procedures were conducted by an experienced Master Certified Coach (MCC) by the International Coach Federation (ICF). All procedures were authorized by the university ethical committee in accordance with the ethical standards laid down in the 1964 Declaration of Helsinki.

### Instruments/Measures

#### Emotiv EPOC+ Headset

An Emotiv EPOC+ EEG neuroheadset device of 14 receptor channels was used to carry out the registering of brain cortical activity. EEG recordings were acquired using the Emotiv Pro software. Data was continuously recorded at a sampling rate of 256 Hz through wet saline that registers cortical electrodes (AF3, F7, F3, FC5, T7, P7, O1, O2, P8, T8, FC6, F4, F8, and AF4) and placed according to the international 10–20 system and two references on the left and right mastoids bones. The wireless EEG device transmits data via Bluetooth through the 2.4 GHz band. It has a sampling rate of 128 bit/s, a bandwidth ranging from 0 to 64 Hz, automatic digital notch filters at 50 and 60 Hz, and the dynamic range referred to the input is 8,400 $\mu$V (pp). Moreover, we evaluated the good EEG signal quality to ensure the accuracy of EEG data collection before starting the EEG signal recording. We did not start the signal recording if its quality was less than 99%.

#### Creativity Self-Assessment Questionnaire

A creativity self-assessment *ad hoc* questionnaire based on a six-point Likert scale (null: 1, very low: 2, low: 3, acceptable: 4, good: 5, and very good: 6) was used to measure the subjective level of creativity of each subject during each experimental condition (R, DC, and NDC). The design of this scale has been based on the concept of creativity and self-perception indicated by Sheth et al. (2009) which, according to insight, can be identified in two ways: By relying on the feeling of "aha!" personal or subjective nature of the individual solving the problem, or by objectively classifying a solution based on a creative cognitive process. In this way, the six levels of the Likert scale sought to facilitate that the participants could more easily discriminate the subjective feeling of the creativity level generated by the different moments of "aha!" during the three experimental conditions (R, D, and NDC). This instrument is a simple scale that was administered at the end of each session to record the subjective level of creativity experienced by each participant during each experimental condition. Questions were configured through a mixed process following the introductory fundamentals and research objectives, and through experts' judgment (Camic et al., 2003).

## Experimental Procedure

Individual coaching sessions were carried out in a quiet room ($3.25 \times 5.5$ m) where electromagnetic radiations were minimized, except those of the EEG instrument itself, video camera, keyboard for subjects, and the computer necessary for data collection. Possible distractions in the room were withdrawn, but two comfortable chairs and a study table to place the computer were available.

The study design was single-blind. In this way, the subjects were not previously aware of the experimental procedure or the specific objective of the coaching session in order to prevent results to be conditioned during the experiments or by possible previous learning experience. Firstly, when each subject arrived, he/she was requested to sit on a chair. He/she was then informed that the three free-choice goals or problems will be addressed in the order that they choose. The researcher also explained the instructions and guidelines of the EEG procedure to ensure good recording (to control eye blinking, sudden movements, and to must keep their body still to avoid EEG recording artifacts). Participants were asked to sign the consent form and an authorization for video recording of the session before starting the experiment. The recording allowed to analyze the relationship between insights, GROW coaching model phases, and the different meta-competencies used. Before placing the neuroheadset on the scalp, the electrodes were slightly wet with saline solution (sodium chloride 0.9%) to improve skin contact and to increase conductivity. Next, the EEG device was over participant's head following the 10–20 standard positioning by the researcher, and the device connection was checked for 100% connectivity (**Figures 1A–C**).

Secondly, once the subject was ready to proceed with the experiment, the researcher started recording the EEG signals. EEG baseline was registered for 30 s with closed and open eyes. Then, the participant is asked to solve the first goal or problem by R (no coaching or interaction with the subject at this stage). After, the participant is guided to achieve the second goal or problem by DC. Finally, the participant is asked, without guidance, to resolve the third goal or problem by NDC (**Figure 1D**). As follows, we explain in more detail each intra-subject experimental condition based on the coaching approaches (**Figure 1D**):

- Rumination (R, no coaching): The subject is asked to think for as long as necessary, without any help or assistance and in silence of possible solutions on how to solve the first problem or goal that he/she has chosen.
- Directive coaching (DC): The subject is asked to raise the second problem or goal, during which the researcher holds a conversation with the subject. Suggestions for the goal, possible advice, and hints on how to arrive at the solution, together with closed questions with an implicit solution are offered while mirroring back the subject's comments with the researcher's own interpretations, without any structure or order designed.
- Non-directive coaching (NDC): The subject is asked to expose the third problem or goal chosen, and the researcher initiates a conversation following the structural competence of GROW and only making exclusive use of non-directive meta-competences (phenomenological perception, focused reflections and questions, all based on non-directivity principles). During this third condition, the researcher pays special attention on not transferring any type of judgment or knowledge to the subject.

During all experimental sessions, each subject was monitored with the Emotiv EPOC+ device, and EEG data were collected and recorded to identify every event of creative insight with one marker (press space bar) for subsequent analysis through EmotivPRO software, San Francisco, CA, United States (**Figure 1D**). As mentioned previously, according to Sheth et al. (2009), insight can be identified in two ways: by relying on the feeling of "aha!" personal or subjective nature of the individual solving the problem or by objectively classifying a solution based on cognitive processes. To identify insight from a cognitive process and not based on the subjectivity of the individual, the focus can be established on the following elements: a mental deadlock or impasse, where the participant is "stuck" and unable to continue (Fleck and Weisberg, 2004); and a construction or creation of a new or hitherto unobvious representation (Ohlsson, 2008). From the psychophysical point of view, in the 4 s prior to the indication of insight by the participants in the non-directive condition, we found significant differences that were observed in terms of the increase in power in the alpha and theta frequencies of the right temporal region. Significant differences were also found in the frequencies alpha, theta, and gamma of the right parietal region, in comparison with the results obtained in the ruminative and directive conditions. The brain regions and frequencies where significant power increases were recorded and coincide, for the most part, with previous studies on the different EEG patterns in the field of creative insight (Jausovec, 1997, 2000; Mölle et al., 1999; Razumnikova, 2000; Aftanas and Golocheikine, 2001; Herrington et al., 2005; Fink et al., 2006, 2011; Sandkühler and Bhattacharya, 2008; Gruzelier, 2009; Kounios and Beeman, 2009, 2015; Fink and Benedek, 2014; Rothmaler et al., 2017; Wokke et al., 2017, 2018; Oh et al., 2020). In addition, these EEG studies are reinforced by other neuroimaging studies that show

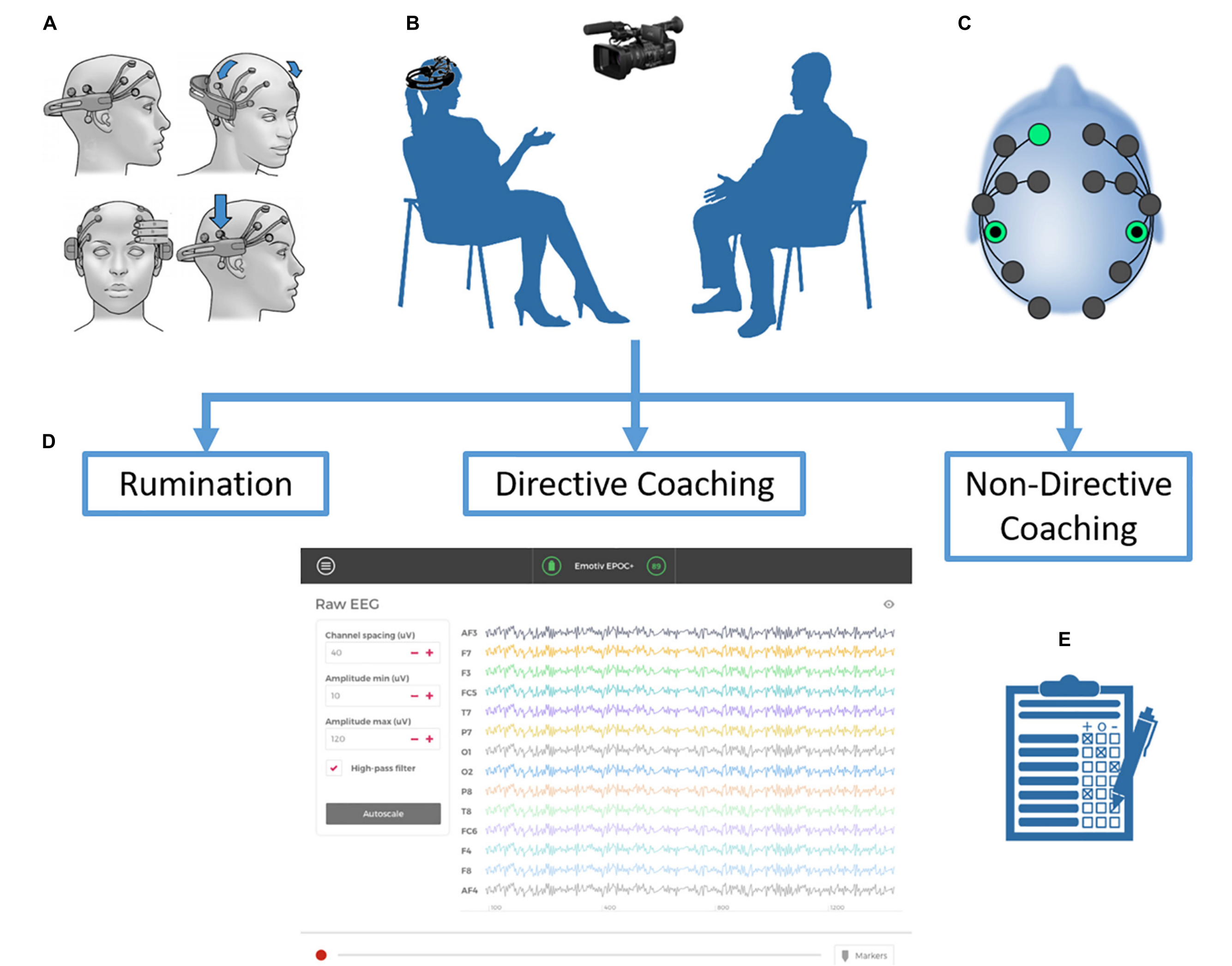


**FIGURE 1 |** Schematic illustration of the experimental procedure performed in each experimental session during electroencephalographic (EEG) acquisition data. **(A)** One wireless EEG device (Emotiv EPOC+) with non-invasive electrodes (14 channels) was placed on the forehead subject according to the International 10–20 system before data-collection. **(B)** Subjects were informed about the instructions, procedure followed during the session (free-choice and order of three goals or problems to resolve) and tips in order to ensure good EEG recording. Each session was video recorded to analyze the relationship between insights and goal, reality, options, and will (GROW) coaching model phases. **(C)** Spatial mapping of the electrodes' current connection status on the scalp (color code: green, good connection; black, not providing information). Data recording was started when all electrodes had good connectivity. EEG baseline was registered with closed and open eyes (both for 30 s). **(D)** Participants were guided during each individual session to resolve a problem by rumination (no coaching), directive coaching, and non-directive coaching approaches while EEG brain activity was recorded, identifying every moment of creative insight (even-related markers). **(E)** After EEG data acquisition, the creativity self-assessment scale was filled out.

evidence of neuronal activity during the generation of insight in the temporoparietal regions (Beeman and Bowden, 2000; Coney and Evans, 2000; Starchenko et al., 2003; Bechtereva et al., 2004; Kounios et al., 2006; Benedek et al., 2016). The basis for an objective consideration of the insight condition would be found in the joint use of these two mentioned parameters. That is, the marks in the EEG reading in which the participants indicated a new and useful idea after a "stuck" situation and an EEG correspondence of the 4 s prior to that mark with the frequencies and regions aforementioned.

Once the coaching session was finished, the recording session was concluded, and the device was removed from the subject's head. Finally, each subject assessed the levels of subjective creativity achieved for each coaching condition responding to the creativity self-assessment questionnaire (**Figure 1E**).

## Statistical Data Analysis

The EEG data were analyzed using the JupyterLab platform. A specific program that works on Jupyter Notebook was created using the Python 3.8 language, which allowed us to perform the data analysis by applying a frequency-time analysis based on Discrete Wavelet Transform (DWT). Five frequency waves ranges were extracted (theta: 4–7 Hz, alpha: 10–13 Hz, low beta: 13–16 Hz, high beta: 16–28 Hz, gamma >32 Hz). To focus on

EEG activity during the three experimental conditions (R, DC, and NDC), the median of the maximum power for each electrode site and frequency waves was analyzed in epochs of 4 s prior to the marker activated (press space bar) by the subjects at the time of the perceived insights manifested in every condition. Additionally, a filtering was performed, eliminating data where the power exceeded ±100 μV and that were related to artifacts from blinks or facial muscle movements.

We ran different comparative analyses to assess the effect of the three experimental conditions (R, DC, and NDC) on dependent variables (number of insights, creativity self-assessment scores, and EEG frequency waves) using the SPSS 22.0 software for Mac. Once the statistical tests of normality were carried out, we used non-parametric statistical tests (Wilcoxon signed-rank test) due to the non-normality of the data. The significance level was set to $p < 0.05$.

# RESULTS

## Insights and Creativity Self-Assessment

When we compared the number of insights registered between experimental conditions (R, DC, and NDC), we found that the subjects showed a higher number of insights during the non-directive condition compared to the other conditions (Directive: $p < 0.003$; Rumination: $p < 0.009$, Wilcoxon signed-rank test) (**Figure 2A**). We also found statistically significant differences comparing the subjective perception of perceived creativity in the creativity self-assessment scale between conditions. Our results showed higher scores in the non-directive condition compared to the other conditions (Directive: $p < 0.047$; Rumination: $p < 0.011$, Wilcoxon signed-rank test) (**Figure 2B**).

## Electroencephalographic Power

After having carried out a comparative statistical analysis between all the electrode sites of both cerebral hemispheres and the different frequencies, the analysis focused on observing the power differences for each EEG wave frequency range (theta, alpha, low and high beta, and gamma) generated in cortical brain regions (frontal, temporal, parietal an occipital) during experimental conditions. This allowed us to observe if there was any significant difference in EEG power between NDC, DC, and R situations during the 4 s before subject's marks of insights. In this channel-based EEG regional analysis, we found significant differences placed in different brain regions (parietal and temporal cortices) of the right hemisphere. The right parietal region (P8) showed a significant increase in EEG power in the alpha and theta frequency ranges between NDC vs. R and DC conditions (Alpha: $p = 0.003$, $p = 0.034$, respectively; Theta: $p = 0.005$, $p = 0.013$, respectively), whereas gamma frequency range also revealed a significant increase of high power between NDC vs. R and DC conditions ($p = 0.023$, $p = 0.041$, respectively) (**Figure 3**). However, although the results of the beta high frequency range in the right parietal region (P8) showed an increase of beta power in the NDC condition, it did not show a significant difference compared to the other conditions. Additionally, the right temporal region (T8) also showed a significant increase of EEG power in theta and alpha frequency ranges between NDC vs. R and DC conditions (Theta: $p = 0.011$, $p = 0.021$, respectively; Alpha: $p = 0.006$, $p = 0.034$, respectively) (**Figures 3**, **4**).

The boxplot analysis represents the median EEG power values associated to creative insights through different levels of activation frequency ranges (theta alpha, beta high, and gamma). We have selected the right parietal (P8) and temporal (T8)

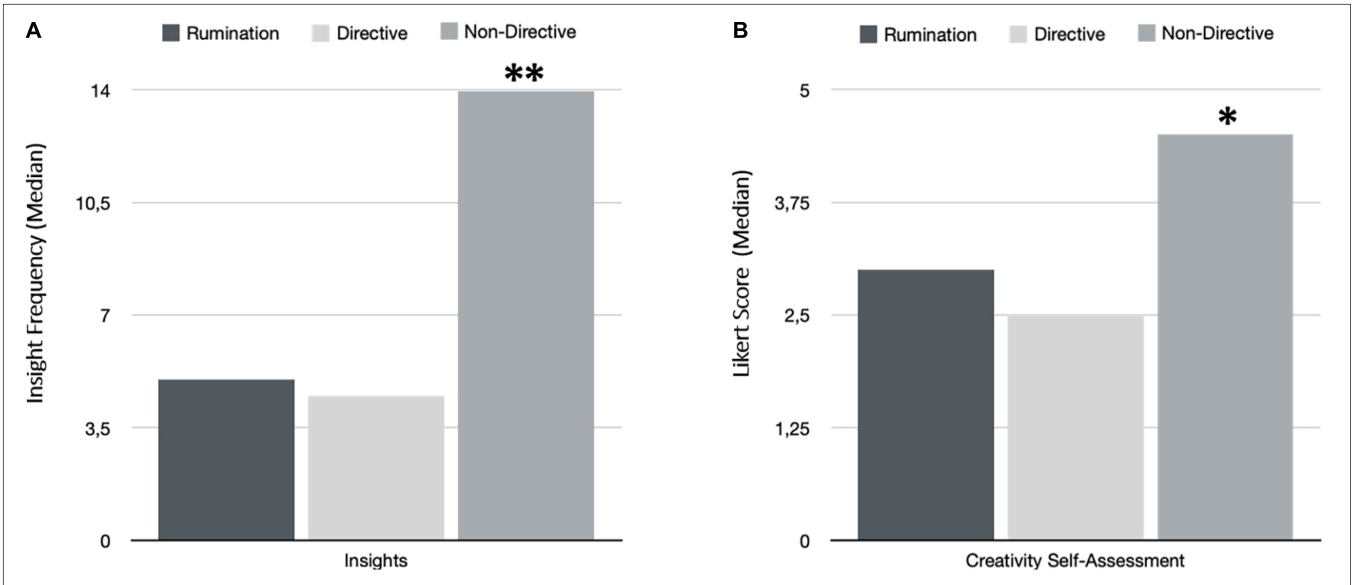


**FIGURE 2 |** Graphics showing the numbers of insights registered **(A)** and the levels of creativity perceived by the subjects **(B)** during each experimental condition evaluated after coaching session. Significant differences can be observed between the greater number of insights and the perception of higher levels of creativity in non-directive coaching condition compared to the other conditions (rumination and non-directive coaching). Insights: **$p < 0.01$; Self-assessment: *$p < 0.05$.

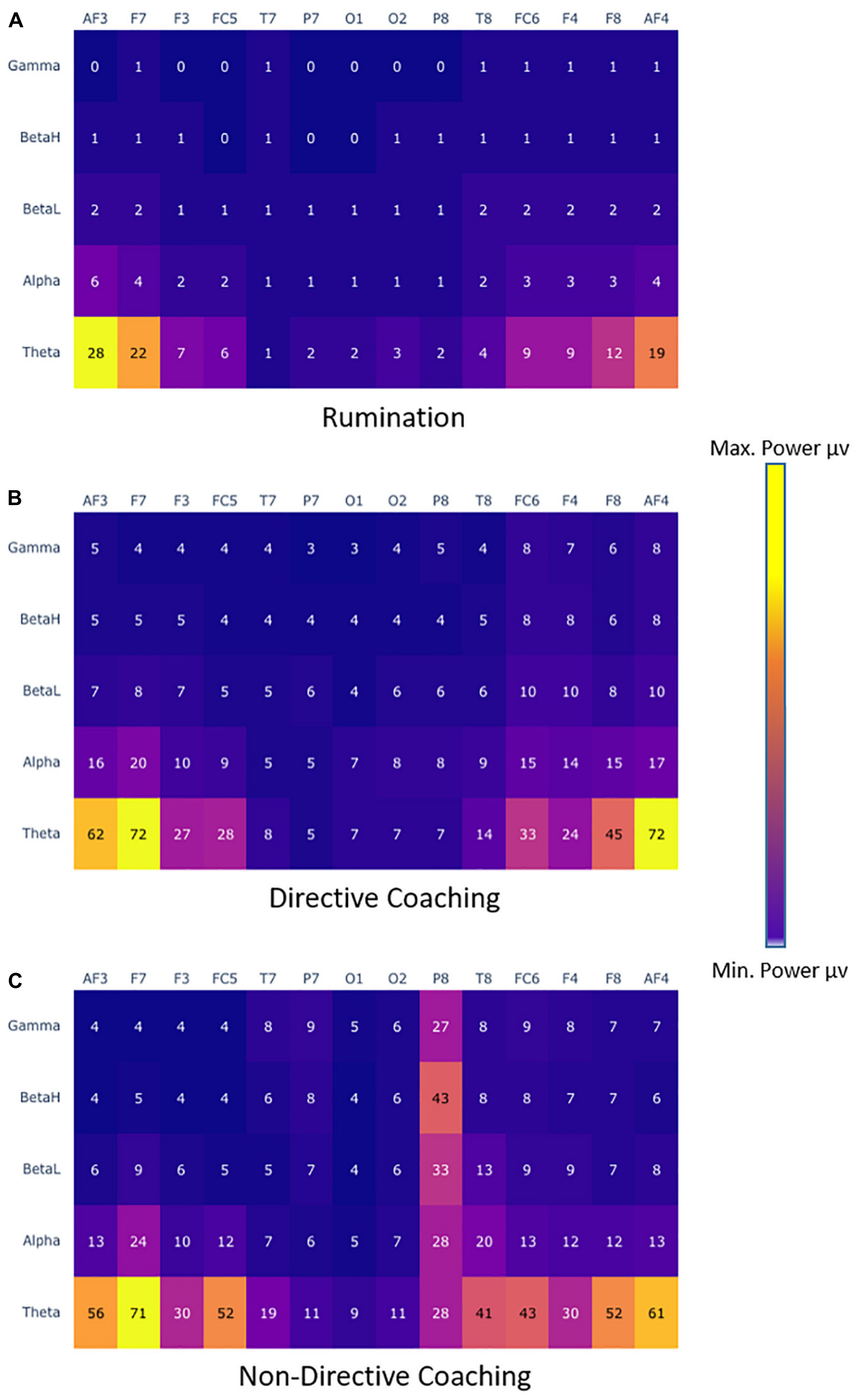


**FIGURE 3 |** Heat map of EEG power generated by insights in each experimental condition [**(A)** Rumination, **(B)** Directive coaching, and **(C)** Non-directive coaching]. Heat maps indicates the magnitude of the effect of EEG power at each frequency band (gamma, beta low and high, alpha, and theta) across 14-EEG channels (AF3, F7, F3, FC5, T7, P7, O1, O2, P8, T8, FC6, F4, F8, and AF4). Colors represent values resulting from the median of the power (µv) for epochs of 4 s prior to the marker activated (press space bar) by the subjects during each condition. Cold colors indicate decrease, whereas hot colors indicate increase in the median of the EEG power for each cortical region (electrode sites) and frequency wave bands.

channels because they showed high EEG power related to creative cognitive activity according to our previous hypothesis, while the right occipital (O2) channel has been selected as the control channel. We showed the distribution of the median EEG power values (µv) associated with events of creative insights during each experimental condition (R, DC, and NDC) placed in the

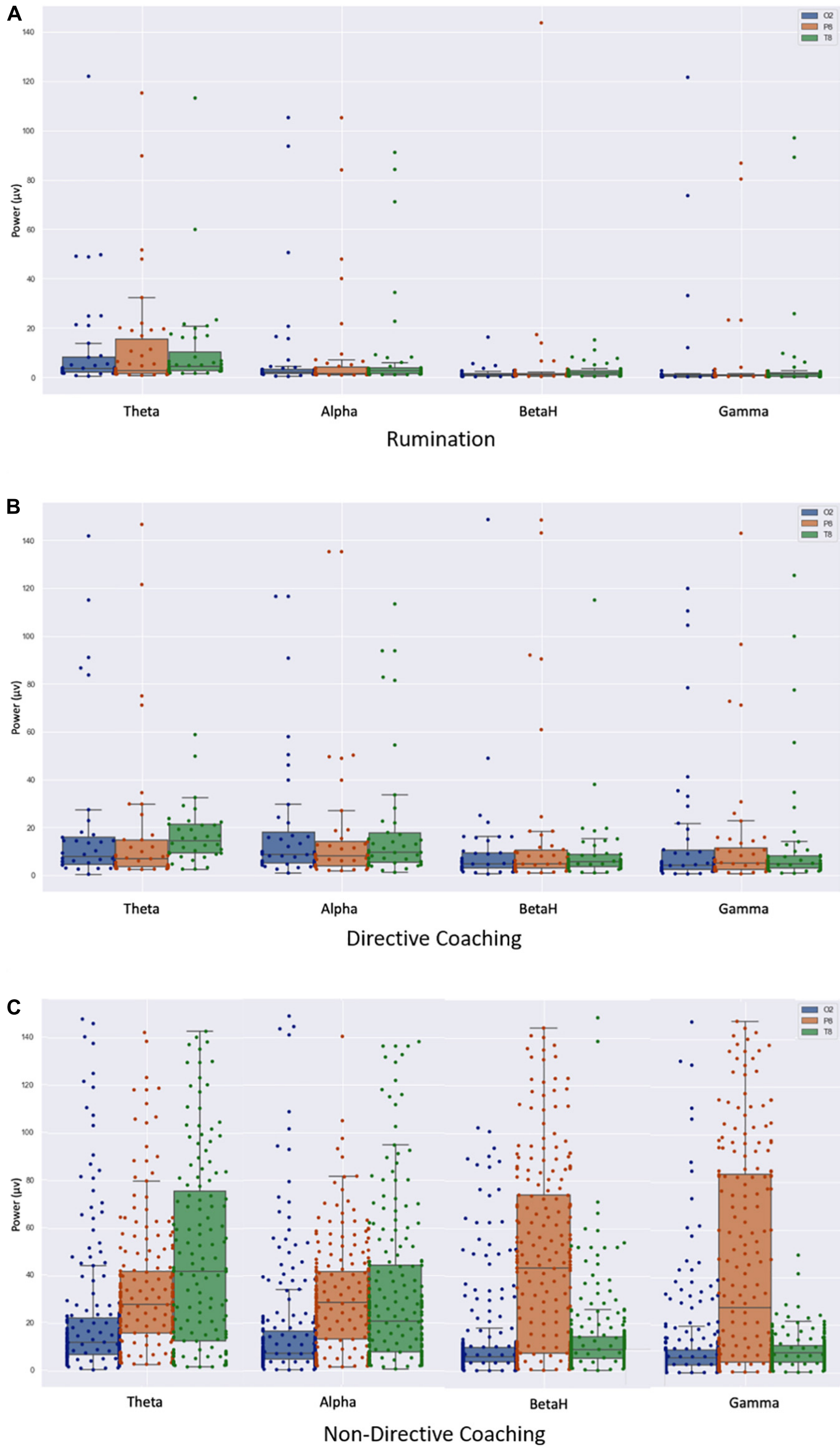


**FIGURE 4 |** Box plots represent medians, interquartile ranges (P25–P75), and min-max (whiskers) of the EEG power during insight time window (epochs) in occipito-parieto-temporal right channels in each experimental condition [**(A)** Rumination, **(B)** Directive coaching, and **(C)** Non-directive coaching]. The graphic shows the distribution of the EEG power associated to insights in the right occipital (blue), parietal (orange), and temporal (green) channels at the theta, alpha, beta high, and gamma frequency ranges during each condition. Creative insights during non-directive coaching condition induced higher EEG power in the alpha and theta frequency bands of the right temporal region (T8), and in the alpha, theta, and gamma frequency bands of the right parietal region (P8). No differences were found in the right occipital region (O2). Within the box, black line represents the median value. Color data points are shown for each selected channel (blue to occipital, O2; orange to parietal, P8; green to temporal, T8).

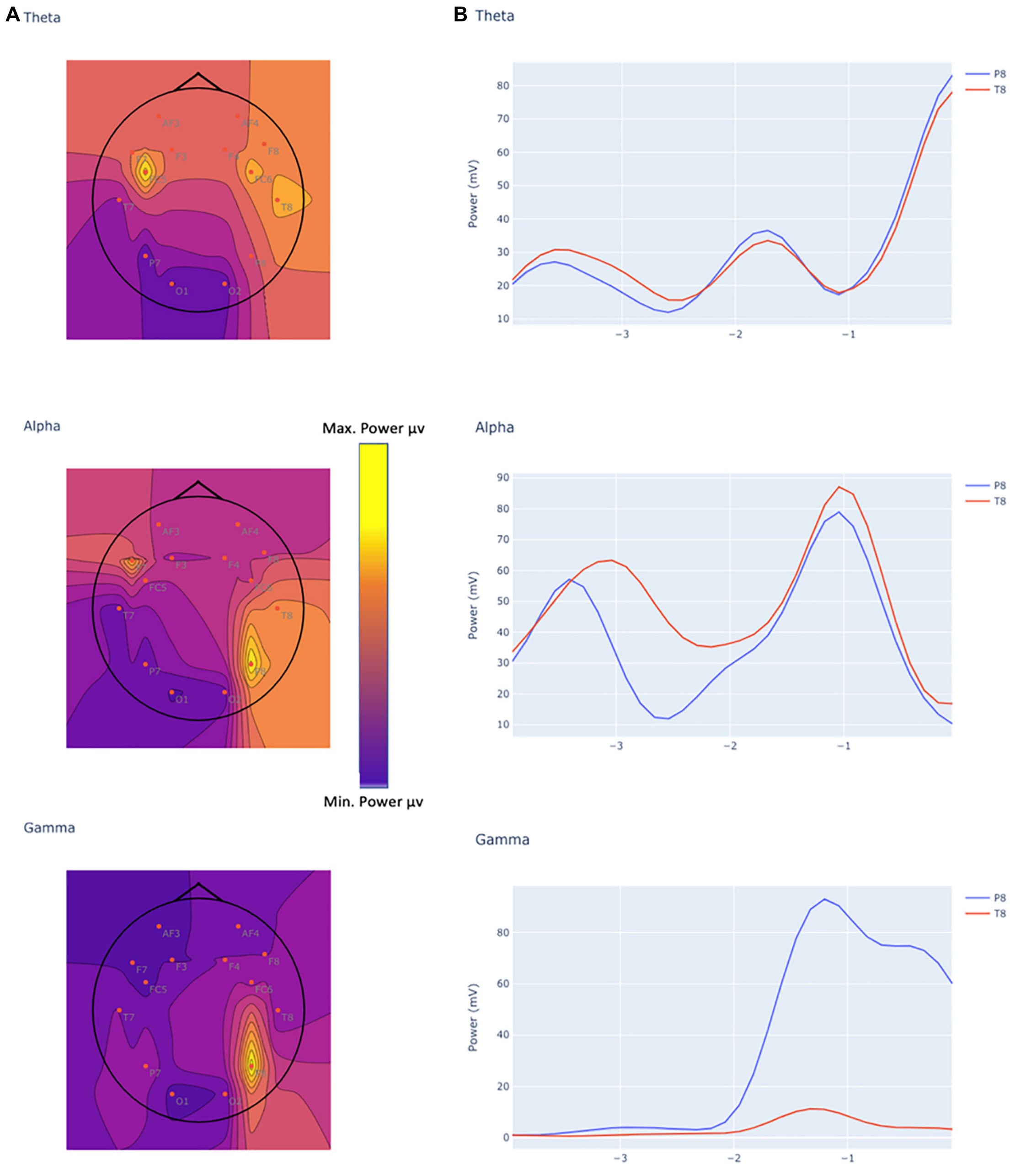


**FIGURE 5 |** Topographic distribution of scalp power to theta, alpha, and gamma frequency bands in the non-directive coaching condition **(A)** and EEG power wave form to alpha, theta, and gamma frequencies in the right temporal and parietal channels **(B)**. **(A)** Graphic showing the spatial distribution of theta, alpha, and gamma frequency bands in relation to their EEG power levels in the 4 s prior to the identification of insights by the subjects in the non-directive coaching condition. **(B)** Representation of the increase in power (µv) in the alpha, theta, and gamma frequencies in the right temporal (T8, red) and parietal (P8, blue) regions during the 4 s prior to the marker activated when one creative was identified by part of the subject.

right parietal (P8), temporal (T8), and occipital (O2) channels for the alpha, beta high, theta, and gamma frequency ranges. We found that there is a significant increase of EEG power in the right parietal (alpha, theta, and gamma) and temporal (alpha and theta) regions related to an increase in the generation of creative insights during the NDC condition (**Figure 4**). It can also be seen that the median values (alpha T8, 20 µv; alpha P8, 30 µv; beta high P8, 42 µv; beta high T8, 15 µv; gamma P8, 30 µv; gamma T8, 10 µv; theta P8, 30 µv; theta T8, 40 µv) associated with the insights fall within the EEG activation frequency ranges (alpha 10–200 µv; beta 1–50 µv; theta 5–100 µv; gamma 1–50 µv) (Tatum, 2008; Guyton and Hall, 2020).

Likewise, we also showed topographical representation of cortical EEG activity, specifically in the right temporo-parietal region associated with the creative insights during the NDC condition (**Figure 5A**). In this sense, we can observe an example of increased EEG power in the theta and alpha frequencies in the T8 channel (red line) and in the theta, alpha, and gamma frequencies in the P8 (blue line) for one epoch (4 s prior to the marker activated, from −3 to 0 s) corresponding to the generation of one creative insight during NDC condition (**Figure 5B**).

## DISCUSSION

The present study aimed to analyze the possible relationship between the use of a NDC approach in solving problems or achieving goals and the generation of creativity/insight processes and their associations with specific patterns of cortical brain activity. Although there is no scientific evidence that analyzes the different coaching approaches while recording cortical activity by EEG, we can find current works that carry out studies of some basic characteristics of and approaches to coaching using functional MRI (fMRI) (Jack et al., 2013; Boyatzis and Jack, 2018). It is also possible to find some articles that develop the field of creativity from the perspective of insight using EEG (Jung-Beeman et al., 2004; Mai et al., 2004; Fink and Benedek, 2014; Stevens and Zabelina, 2019). Despite this, to date, this is the first work that analyzes the generation of creative insights under NDC approach and their relationship to cortical patterns of brain activity measured by EEG band frequencies.

Kounios and Beeman (2009) define insight as a sudden understanding that solves a problem or reinterprets a situation, but, due to its immediacy, seems to be disconnected from the immediately preceding thought. These authors consider insight as one of the essential elements necessary for the culmination of the creative process, which is also part of the basic abilities of the human being (Kounios and Beeman, 2015). Our results allow to relate the number of insights per condition and the levels of perceived creativity in the creativity self-assessment scale. The difference appreciated in these measures that compare the three experimental conditions is favorable in both cases in the NDC. The increase in the number of insights registered by the subjects and the increase in the level of creativity subjectively perceived by each participant seem to be related to the application of the GROW model as a structural competence for the effective application of the NDC condition. In a recent study, Oh et al. (2020) made a direct association between the gamma frequency activation and the moment before the insight starts with a greater reward sensitivity. We also found an increase in the gamma frequency placed in the right temporoparietal region that was related to the 4 s prior at the moment of insight. In this sense, it is deducible that the approach of the first phase of the GROW model, objective (G), to identify those positive and beneficial aspects that the subject wants to achieve, increases the reward sensitivity and therefore facilitates the path toward the generation of insights (Kounios and Beeman, 2015).

Regarding the field of insight and EEG activity, our results showed an increase in alpha power recorded in the right temporal and parietal region. Previous studies had also already confirmed the relevance of the alpha frequency range induced by processes of creative ideation (Mölle et al., 1999; Jausovec, 2000; Razumnikova, 2000; Agnoli et al., 2020). In this sense, Fink and Benedek (2014) claim that most studies reveal that the creative process can be characterized by an increase in alpha power in the prefrontal and posterior parietal regions of the right hemisphere, which partially coincides with the data recorded in this experiment. Furthermore, other studies from this same group suggested that alpha power range increases as a result of interventions aimed at increasing creativity (Fink et al., 2006, 2009, 2011). Our results also showed an increase in gamma power range in the right parietal region which was associated with the emergence of creative insights. Kounios and Beeman (2009) and Oh et al. (2020) showed how the EEG recording detected a significant increase in high frequency (40-Hz, gamma frequency band) 300 ms before the subjects pressed the button to indicate that they had found a new solution to the given problem. This increase in gamma frequency was placed in the registering electrodes located on the right anterior temporal lobe (Kounios and Beeman, 2009). Another study developed by Sheth et al. (2009) found an improvement in the gamma power band (30–70 Hz) placed in the right cerebral hemisphere (frontal, frontal-medial, and temporo-medial regions) when participants correctly solved one problem (verbal puzzles task) through insights and reported experiencing an "Aha!". In our study, the increase in gamma power associated with creative insights is placed on the right parietal region. This apparent discordance may be due to the limitation of our EEG device, as it only had 14 channels receptors, or to the difference between both cognitive tasks. Despite this, there is a certain close proximity between the channels located in the temporo-parietal region and in both cases that are located in the right hemisphere.

Similarly, Sandkühler and Bhattacharya (2008) identified correlations in EEG activity between the four elements of the insight solution process, namely, (1) deadlock, (2) restructuring of the problem representation, (3) deeper understanding of the problem, and (4) "Aha!" feeling of immediacy and obviousness of the solution. This study shows considerable similarity to the results presented in our research. First, an intense response of the gamma power range was found in the parieto-occipital regions that were interpreted as an adjustment in selective attention processes (leading to a mental deadlock or a correct solution depending on the power level of the gamma band) and a coding of the recovery processes for the emergence of new spontaneous solutions. Second, they observed an increase in the high alpha power range placed on the right temporal regions (suggesting a suppression of the weakly activated solution of relevant information) for initially unsuccessful attempts that which after the presentation of a track led to a correct solution. The analysis of theta frequency power showed an increase in the right temporal and parietal regions associated with creative insights. In this sense, Wokke et al. (2017, 2019) showed how creative metacognitive and decision-making processes are orchestrated by oscillations of theta frequency in the prefrontal cortex. Moreover, this research group demonstrated that high creativity is associated with an improvement in long-range functional connectivity between the occipital and medial prefrontal cortex. Furthermore, Von Stein and Sarnthein (2000) described that during top-down processing of internal information, slow theta and alpha frequency ranges shows long-distance synchronization between the fronto-parietal regions. Other studies also support this approach by relating the increase in low-power waves with coherence in theta frequency range between long-distance connections (Aftanas and Golocheikine, 2001; Herrington et al., 2005). Thus, Gruzelier (2009), by relying on data provided by various investigations (Petsche, 1996; Aftanas and Golocheikine, 2001; Thompson et al., 2008), hypothesizes that creative cognitive associations arise from integration through the co-activation of activity slow waves, such as theta and low alpha frequency ranges of widely distributed neural networks.

In addition to the EEG studies mentioned above, we can also find some neuroimaging studies that provide evidence of neuronal activity during insight in the temporoparietal regions, emphasizing the importance of these regions over the frontal regions (Starchenko et al., 2003; Bechtereva et al., 2004; Kounios et al., 2006; Benedek et al., 2016).

## CONCLUSION

In relation to the achievement of the specific objectives of this work study, our conclusions claim that: (1) The right application of the NDC meta-competencies together with the GROW structural competence facilitate the emergence of insights and, therefore, the generation of creativity processes; (2) There is a relationship between the generation of a greater number of insights and the subjective perception of greater creativity shown by the participants in the NDC condition compared to the other conditions (R and DC); (3) The application of the methodological framework of the NDC induced a higher EEG activation of electrode sites in the parieto-temporal cortical networks of the right hemisphere; and (4) Our results show significant changes in the right parieto-temporal cortical brain regions that are associated with the generation of insights during NDC. EEG power activity was higher in alpha and theta frequencies in the right temporal region, and alpha, theta, and gamma frequencies in the right parietal region during creative insights in NDC compared to other experimental conditions (R and DC). The study provides a new perspective on the application of NDC to insight into creative processes. It would be possible that the emergence of meta-cognitive processes allows the potentiation in the generation of creative insights to solve problems and to improve the development of human knowledge.

One of the aspects that has limited the possible scope of the results is produced by use of a commercial portable 14-channel EEG device. It is understood that although the device used has the scientific validation necessary for its use in experimental research (Badcock et al., 2013, 2015), it is very likely that having more receptor channels would have allowed us to specify more and better, especially regarding the spatial location of the EEG wave changes. It is also interesting to note that wired EEG devices have a higher level of precision than wireless ones, and that clinical EEGs have a higher level of reliability than commercial ones. All this could have facilitated obtaining results that are even closer to those of other studies previously carried out.

We believe that it could be interesting, as a future line of research, to transfer the object of the study to the scope of the coach's brain and analyze how the EEG patterns associated with creativity in performance influence the use of meta-competencies. In this way, it could be investigated if the elaboration of questions and reflections is based on a convergent thought dynamic or if, on the contrary, it is the result of divergent thinking and insight. Deepening in this area could provide very useful information to understand how to generate the meta-competencies of the NDC more effectively by the coach and lead to better practice in the profession.

Additionally, it is important to broaden the scope of this research to study the impact of the NDC process on the improvement of the creative capacity of people in the medium and long-term. It is also important to broaden the scope to study the possible developments of creative autonomy in the brain without having to depend on the external elements of the coach for the generation of creative solutions once the coaching process is finished. This study would help validate whether the NDC process can establish a habit in accessing the brain's mechanisms of creativity without the need to consciously generate the entire competence and structural process.

## 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 CEIM – Hospital Universitari Arnau de Vilanova. Code: CEIC-2499. The patients/participants provided their written informed consent to participate in this study.

## AUTHOR CONTRIBUTIONS

EB and CT-N: conceptualization, writing – original draft preparation and reviewing and editing, formal analysis, and methodology. GB: writing – original draft preparation and reviewing and editing, formal analysis, methodology, and software. SV: methodology and software. All authors contributed to the article and approved the submitted version.

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