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External mediation educational resources for teaching General Relativity: a systematic review

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ABSTRACT
Modern and Contemporary Physics is an important component of civic education for senior high school students, as topics such as Relativity and Quantum Physics connect with everyday life and foster abstract thinking and critical skills. Yet, these themes are often absent from high school curricula. Among them, Einstein's General Relativity Theory (GR) stands out: when presented, it usually sparks strong student interest. This paper aims to support GR teaching through a systematic literature review that identifies accessible resources for high school classrooms. The review is framed by the Cognitive Mediation Networks Theory (CMNT), focusing on its external mediation levels. Searches were conducted in ERIC, Scopus, Google Scholar, and SciELO, targeting studies reporting resources that are both accessible and manipulatable, enabling students' external information processing. Thirty studies met the criteria, comprising resources across psychophysical (14), social (2), cultural (4), hypercultural (10), and sophotechnic (2) mediations. These ranged from physical models, analogies, and collaborative discussions to cultural artifacts, simulations, and AI chatbots. Some gaps were identified: several studies described GR resources without robust empirical testing, while others offered limited evaluation. This suggests that GR teaching at the high school level is still at an early stage. The review highlights the diversity of educational technologies available and their potential to expand students' cognitive capacity through CMNT mediations. Although centred on a specific topic, the mediation-focused analysis proposed here offers a model for identifying effective instructional technologies applicable to teaching other complex theoretical concepts.

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Introduction

Developing informed citizens with critical thinking skills is a key educational goal for full participation in a modern and complex society (Muhfahroyin et al., 2024). Scientific literacy is crucial, and certain science topics, like Modern and Contemporary Physics (MCP), can facilitate this by providing new perspectives and understanding of everyday technologies (Boublil et al., 2023). MCP topics engage student interest (Emrahoğlu & Yalçın, 2025; Henriksen et al., 2014), especially Einstein's Relativity Theory, which is further motivated by its astronomy links (Kersting, 2019).

The development of relativity has led to the emergence of widely used technologies such as the Global Positioning System (GPS) and events such as the detection of gravitational waves (Abbott et al., 2016). The first image of a black hole increased the presence of General Relativity (GR) in social media (Bower & Van Langlevende, 2022), bringing GR closer to students' daily lives. Therefore, including GR in the school curriculum can help 'overcome negative attitudes towards science' (Aristeidou et al., 2023).

However, the abstract reasoning required to understand the complexity of GR most often excludes it from the secondary science curricula worldwide (Kaur et al., 2017), largely because the relativistic effects are not observed in daily life and conflict with various common-sense ideas (Kraus, 2008). In this sense, the main student difficulty is related to visualization of relativistic phenomena. For example, students often struggle in their imaginative processes due to tensions between their understanding of previously learnt Newtonian conceptions of gravity and their more recent understanding of gravity from an Einsteinian perspective (Steier & Kersting, 2019). Not surprisingly, this difficulty in the abstraction process that requires students to learn about GR was also observed when primary grade students were introduced to this concept (Ruggiero et al., 2021).

Even undergraduate physics students have difficulties understanding GR concepts. Classical conceptions from other conceptual domains, such as Galileo's Relativity, challenge students' understanding of GR (Bandyopadhyay & Kumar, 2010). Students also have difficulties comprehending inertial reference frames and confusions between Special and General Relativity are common (Gousopoulos et al., 2015). Therefore, to help make GR more easily understood by students, we highlight the importance of activities that stimulate students` imaginative process to overcome these obstacles from previous daily experiences.

Considering this scenario, enriching the learning experience with visualizations of studied phenomena will be highly beneficial. Using various educational technologies based on the Cognitive Networks Mediation Theory's (CNMT) external mediation levels (Souza et al., 2012) has the potential to facilitate students' learning (Authors, 2020).

Therefore, the purpose of this review is to identify educational resources for teaching GR that are supported by the four mediation levels of the CNMT. Consequently, we address the following questions:

- Q1. What are the target levels of instruction in the studies investigating educational resources for teaching General Relativity?
- Q2. What types of educational resources and interventions are used/proposed to teach General Relativity based on different levels of mediation?
- Q3. How can the educational resources using different levels of mediation facilitate students' understanding of General Relativity?

We provide insights into these technologies and approaches, discussing their efficacy in demonstrating GR's complex phenomena, to help teachers engage students more effectively. While topic-specific, this resource analysis has multidisciplinary potential for various school subjects, since it can be replicated for other complex topics.

Cognitive Mediation Networks Theory (CMNT)

The Mediation Cognitive Networks Theory (CMNT) posits that the incorporation of Information and Communication Technologies (ICT) in society has changed individuals' cognitive structure. People develop knowledge by processing information in their brains. However, for complex tasks, engaging with external structures is necessary to enhance brain's capacity through external information (Souza et al., 2012).

This interaction with external structures is enabled through four different mediations: psychophysical (interaction with objects), social (interaction among individuals), cultural (use of language and communication), and hypercultural (using computer and digital tools) (Souza et al. 2012).

Interacting with these external structures, or educational resources, the individual develops internal mechanisms to understand the operations and information provided. Engaging in these mediations is a learning process (Souza et al., 2012), necessitating the development of strategies to optimize their use.

For GR, external processing tools are crucial as it deals with an inaccessible four-dimensional spacetime (Kaur et al., 2017). Therefore, the need arises within the education community to create and disseminate cognitive techniques and tools that can assist the teaching process at different levels and enhance the learning opportunities.

Method

The literature review was developed in November of 2023, through the platforms ERIC, Scopus, Google Scholar and SciELO, widely used sources in science education. On ERIC, a database focused on science education, only the term 'general relativity' was used. We selected these databases for their broad coverage of educational research (ERIC), diverse scientific literature (Scopus), accessibility to a range of materials (Google Scholar), and focus on Ibero-American contexts (SciELO), thus ensuring a comprehensive and culturally diverse dataset.

On Scopus the words in the title, abstract, and/or keywords were searched using the terms and operators 'general relativity' AND ('teaching' OR 'learning' OR 'education'). For Google Scholar, we applied the same terms and operators used at Scopus, both in English and Portuguese. As the most accessed and cited papers are presented in the first pages of Google Scholar, the first 20 pages were analysed. On SciELO the same terms and operators of Google Scholar were used, for both English and Portuguese.

As the aim of the review was to identify teaching resources, we considered papers published from 2000, as older approaches might be outdated. This criterion was established to ensure relevance to contemporary educational technologies, acknowledging that significant growth in digital and external mediation tools occurred after the turn of the century. This systematic review followed the guidelines of the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) (Dewi & Rahayu, 2024; Moher et al., 2015). The first selection of the papers was conducted through the reading of the titles and abstracts. The complete selection process is summarized in Figure 1.

In the screening and reading process, we looked for easy to manipulate resources that could be used with easy-access materials, both for teachers and students, to facilitate GR's comprehension. Considering the CMNT, only papers presenting resources that provided students with an opportunity to engage in external processing of information were considered. Moreover, we considered papers only written in English, Portuguese, and Spanish. Table 1 summarizes the inclusion and exclusion criteria.

Four Mediations Levels' Use

After the selection process, the 30 papers were read in full by the first author to extract the relevant information: the educational technology used/proposed with its external mediation level, the target audience, and, for tested resources, the main research outcomes. To ensure validity and reliability in the article selection and categorization, we implemented a two-stage consensus approach. Any discrepancies in the categorization of this extracted information were discussed between the first two authors until a consensus could be established. We focused on systematically synthesizing qualitative patterns to ensure trustworthiness and transparency of the analysis

The selection and categorization of the papers followed the CMNT premises, considering the external mediation resources that can allow information processing outside the brain. Considering this theory-based analysis and the consensus between the authors, it was possible to increase the validity and reliability of the analysis. This approach helped minimize subjective bias in classification. The categorization process is summarized in Figure 2.

Figure 1

Flowchart of the search and selection process

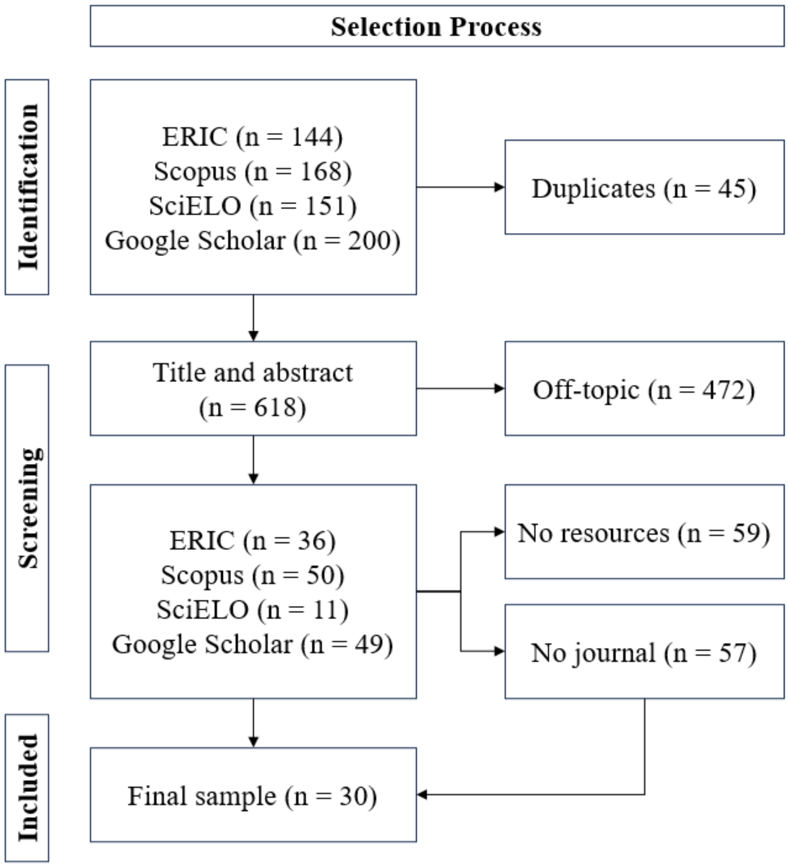


Table 1

Inclusion and exclusion criteria

Inclusion Criteria	Exclusion Criteria
Journal papers	Conference papers, theses, chapters, books
Papers in English, Portuguese, or Spanish	Paper in other languages
Accessible materials and resources	Difficult to access resources
Teaching resources using at least one level of mediation	No specific teaching resources using one of the four mediation levels

Consequently, it was possible to identify studies that reported or proposed the use of each of the four mediations levels (Table 2). Studies were classified according to the most relevant mediation identified, although in some studies more than one mediation level was used. It is possible to note that there is an emphasis on the usage of psychophysical and hypercultural mediations. In contrast, concerning the social mediation only two correlated works were found.

Figure 2

Flowchart of categorization process

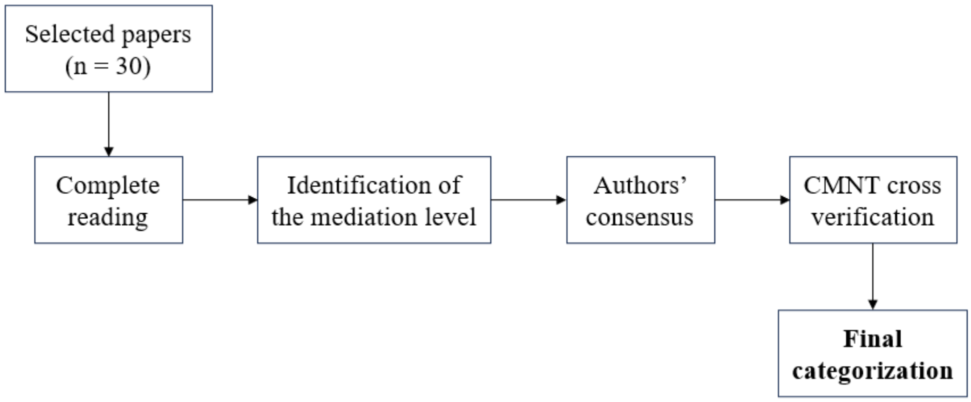


Table 2

Synthesis of selected papers

Source	Psychophysical	Social	Cultural	Hypercultural
ERIC (n = 16)	7	2	0	7
Scopus (n = 9)	6	0	1	2
SciELO (n = 2)	0	0	1	1
Google Scholar (n = 3)	1	0	2	0
Total (n = 30)	14	2	4	10

Results

To present and discuss our results in a logical manner, they were classified according to the external mediation and resource used or proposed.

Psychophysical Mediation

This section focuses on the identified educational resources that enable psychophysical mediation stimulating individuals' sensorimotor schemes.

Sector Models

Zahn and Kraus (2014) presented 'sector models' as a psychophysical resource to visualize curved spacetime in GR (Kraus & Zahn, 2015). The models represent curved surfaces in two and in three dimensions through extrinsic visualization – from one outside observer.

The two-dimensional sector models can be used to identify curvature as positive (spherical space) or negative (hyperbolic space) (Figure 3) by comparing gaps between pieces; for a plane space there are no gaps, a spherical space shows 'open' gaps, and a hyperbolic space shows 'closed' gaps. Three-dimensional sector models represent a three-dimensional plane (Euclidean) and curved spaces (black hole's surroundings) (Figure 4) also with gaps indicating curvature. Therefore, this model allows an extrinsic visualization of a curved three-dimensional space.

Extrinsic visualization of surfaces containing more than two dimensions is challenging. Humans have an intrinsic understanding of three-dimensional space but struggle to visualize it extrinsically, as an additional dimension would be required. Regarding GR, it uses a four-dimensional spacetime universe, and humans cannot perceive the fourth dimension (time) even intrinsically.

Figure 3

Representative scheme of two-dimensional sector models representing the spherical (A) and hyperbolic space (B)

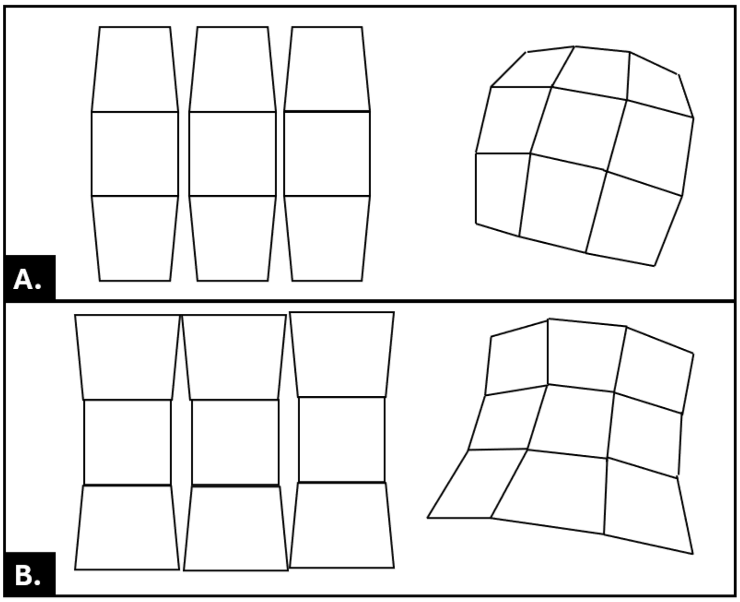
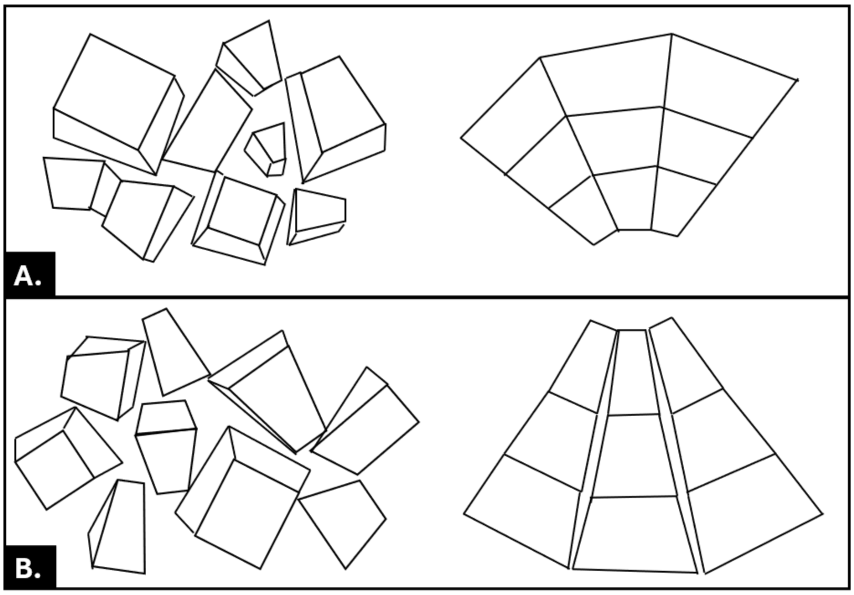


Figure 4

Representative scheme of three-dimensional sector models, separated (left) and assembled (right), representing plane (A) and curved space (B)



Therefore, the human brain is unable to process this kind of information alone and external mediation resources are necessary for students to visualize and comprehend curved spacetime (Souza et al. 2012). Sector models enable the extrinsic view for three dimensions through psychophysical external mediation, aiding students' understanding of four-dimensional curved spacetime.

The authors used these models in subsequent works to represent geodesics and gravitational time dilation (Zahn and Kraus 2019; Kraus and Zahn 2019) and in workshops with pre-service physics teachers and high school students.

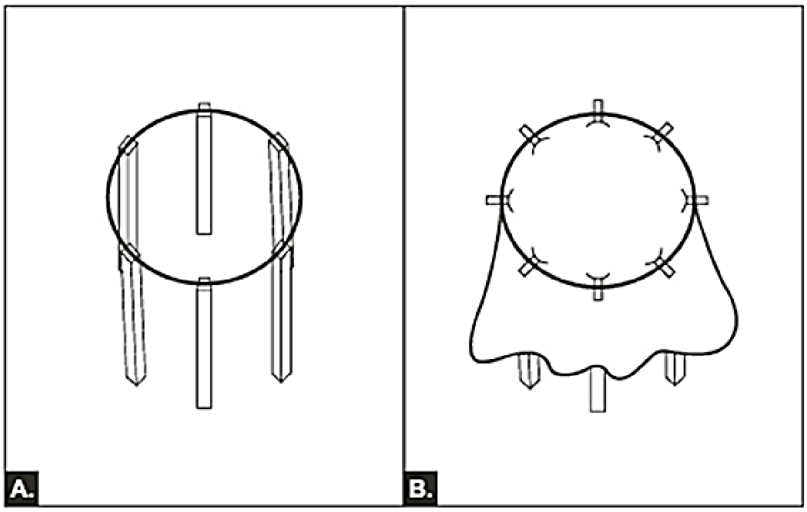
Rubber-sheet Model

The rubber-sheet model is a well-known psychophysical resource used to visualize relativistic phenomena. The Einstein-First project (Einstein-First Project, n.d.) extensively used this model, calling it 'spacetime simulator', proposing various activities to teach Einsteinian physics in schools (Kaur et al., 2017). These activities include measuring spacetime distortion caused by masses (marking two dots on the Lycra-sheet and measuring the distance between them), observing small balls' and toy cars' movements around a central mass, exploring gravitational lensing and precession, measuring gravitational 'force' (using a spring balance with a test mass), and discussing non-Euclidian geometry using triangles on curved surfaces.

Ruggiero et al. (2021) also used the rubber-sheet model and triangles in curved ballon surfaces with elementary school students (10 and 11 years-old). Postiglione and De Angelis (2021a, 2021b) provided a step-by-step guide for constructing a Lycra-sheet structure (Figure 5) and proposed activities through a free-access e-book and activity cards. However, they observed some misconceptions among high school students, such as the belief that only large masses deform spacetime and that gravity acts 'downwards'. Interestingly, the use of this analogy is also reported by Baldy (2007) with Grade-9 students using a soft pillow. The analogy was compared to the traditional teaching methods for teaching falling bodies.

Figure 5

Representative scheme of the proposed structure without (A) and with Lycra-sheet (B)



Despite its limitations, the rubber-sheet analogy is a simple and adaptable resource that can assist students in visualizing GR consequences. It enables the visualization of an effect that students cannot experience in everyday life, serving as an external psychophysical tool that helps students' brains process information (Souza et al., 2012). However, to avoid the development of students' misconceptions, teachers must explicitly discuss the analogy's limitations, such as the visualization of deformation in two spatial dimensions and the need of Earth's gravity for the demonstrations.

Falling Objects

Boublil et al. (2023) from the Einstein-First research group, reported activities with falling objects to explain the Equivalence Principle to Grade-7 students. This principle states that a gravitational field is indistinguishable from an accelerated reference frame, and an inertial reference frame is equivalent to free-fall.

The activities included observing a suspended slinky spring being dropped (its bottom only starts moving downwards when the section above is relaxed), a filled cup of water with a hole in the side (when the cup is dropped, the water stops leaking), a flexible dumbbell (metal measuring tape with a piece of wood on each end), and repelling magnets (toroidal magnets fitted to a wooden dowel rod). In free-fall, the objects behave as if there was no gravity.

These activities help students understand the fundamental concepts of Einsteinian gravity and free-fall. However, students often struggle with reference frame changes and may hold ideas of an absolute and privileged reference frame. These difficulties can hinder students' understanding of the experiments, so it is important to analyse them in different ways.

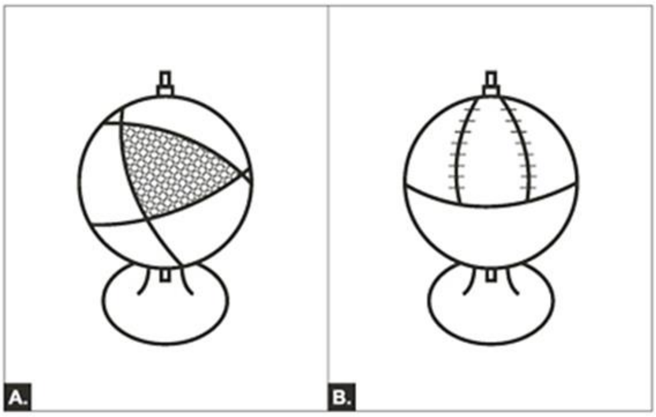
The activities presented used simple psychophysical tools to address the Equivalence Principle, the starting point for GR. The abstract idea of free-fall being equivalent to the absence of a gravitational field involves reference frame changes and can be observed using these external resources, helping the brain's information processing (Souza et al., 2012). The variety of experiments allows teachers to choose the most suitable ones for their context.

Metallic Globe

Andersen (2020) proposed using a metallic globe to convey physical and mathematical concepts to introduce GR. The first activity involves measuring the curvature of the globe using small magnets to form a triangle (Figure 6, left) and calculating the two-dimensional curvature using geometry. The second activity involves drawing six triangles of decreasing sizes inside the marked triangle and comparing their hypotenuse measurements to the calculated values using Euclidian geometry for flat and spherical forms, demonstrating the need for a different geometry on curved surfaces.

Figure 6

Representative scheme of the first activity, with the magnets and strings positioned at the globe (A); and of the third activity, with the geodesic drawn in the globe (B)



The third activity demonstrated the connection between spacetime curvature and tidal acceleration using the 'flatlanders' thought experiment (Thorne, 1994). Two points are marked on the equator of the globe and geodesic lines are drawn towards the pole (Figure 6, right), showing how the lines converge. This demonstrates, in a two-dimensional form, how gravity can be interpreted as a consequence of spacetime geometry (extrinsic view), rather than as a force (intrinsic view). The resources used are accessible and suitable to be used both with high school and undergraduate students.

As the universe is approximately flat in small pieces, the Euclidean geometry works well in everyday life, but the universe is curved on a large scale, requiring a curved geometry. The globe helps visualize abstract and unfamiliar concepts of non-Euclidian geometry, acting as an external psychophysical resource that aids students' information processing (Souza et al., 2012).

Swirling Water Vortices

Barr et al. (2016) compared black holes to swirling vortices in water, an analogy that can be easily used with high school students. Light beams directed to the vortex bend around it due to refraction, forming a shadow, illustrating how light bends around a black hole due to gravity.

As we do not deal with objects as massive as black holes in daily life, it is not possible to easily observe light bending. This simple and accessible resource helps students process information related to light-bending phenomenon through psychophysical mediation (Souza et al., 2012). However, it is important to highlight that this resource is a 'visual metaphor' and does not represent the explanation for light bending.

Seatbelts

Oliveira et al. (2019) proposed activities that establish a relationship with students' daily life experiences, allowing psychophysical mediation. They used traffic education to introduce GR by linking the Equivalence Principle to the need of seat belts. Using an external reference, the passengers' bodies move forward due to inertia when the vehicle stops. However, using the moving vehicle's reference frame, an 'Einstein's force' emerges as a local gravity pulling the passengers' bodies forward. By changing the reference frame, it is possible to demonstrate the equivalence between gravity and acceleration.

Students often face difficulties with reference frame changes when analysing physical situations (Di Casola et al., 2015), which can be an obstacle that teachers need to be aware of when using this comparison between inertia principle and Equivalence Principle. The authors argue that the relevance of this approach is because it covers two important themes: traffic education and Modern and Contemporary Physics. Moreover, the activities can be conducted with students from the final years of elementary school. The strategy uses students' everyday experiences, such as being inside a vehicle, to assist students in information processing (Souza et al., 2012). This is an excellent and simple psychophysical approach for teaching GR.

Wineglass Base

Huwe and Field (2015) presented a simple resource, a broken-off wineglass base with the centre covered with black tape, to allow the visualization of gravitational lensing effects. The activities, suitable for high school students, involve using the wineglass base and graph papers to understand gravitational lensing via an optical lens model.

The resources are easily accessible and simple to use, making this wineglass base a good psychophysical resource enabling external processing to visualize a phenomenon not seen in daily life. However, as the water vortices, it is a visual metaphor for understanding the concept but does not provide the explanation of gravitational lensing.

Experimental Eclipses' Data

Finally, Goldoni and Stefanini (2020) experimental astronomical data about solar eclipses for explaining light-bending. The first substantial confirmation of GR was the light-bending observation during the Sobral Eclipse in 1919. In the following years, more eclipses were observed with the same purpose. The authors collected measurements from eight solar eclipses between 1919 and 2017 and proposed an activity for high school students to compare the data to two different theories, without referring to them as Newtonian or Einsteinian theories.

Students usually present some difficulties in doing calculations (Machado & Santos, 2004) and, considering the small values involved, they can struggle with it. However, using these data can help students comprehend the broader application of Einstein's theory compared to Newtonian gravity. Although it is a group activity (social mediation), the primary emphasis is on psychophysical mediation.

Social Mediation

Even though individuals' interactions can be present in the use of other mediations, in this section we present the activities focusing on the social interaction.

Conceptual Group Discussions

Steier and Kersting (2019), as part of the ReleQuant project (University of Oslo, Department of Physics, 2016), emphasized the role of imagination as a social process that helps students understand abstract complex themes in science education. They analysed the dialogue and gestures of two high school students performing activities related to the rubber-sheet analogy, focusing on the forms of imagination that emerged from collaborative engagement, with words and gestures mediating the imaginative process.

The main students' challenges highlighted are that GR's effects are hardly noticeable in everyday life and the need to learn how to use three-dimensional representation systems. As students faced challenges that their brains were not able to process alone, interaction with external resources, such as the classmates, was necessary to expand their cognitive capacity (Souza et al., 2012). The communication through dialogues and gestures assisted in information processing, highlighting the importance of social mediation during learning.

In another study as part of the ReleQuant project, Kersting and Steier (2018) investigated students' interactions through a metaphor and thematic analysis of written answers from students' groups discussions about the rubber-sheet analogy. They concluded that the social interaction was crucial for students to make sense of abstract concepts and highlighted the importance of providing opportunities for collaborative and creative activities that foster their understanding of curved spacetime.

Hence, we have highlighted the importance of activities that encourage discussions and interaction among students about GR's main concepts. Through social mediation among themselves and with the teacher, students can expand their cognitive processes and better understand GR (Souza et al., 2012).

Cultural Mediation

Cultural mediation is established using symbolic systems that are socially constructed. Incorporating cultural artifacts, like movies and books, into the teaching can aid students processing information.

Science Movies

Moura and Vianna (2019) and Almeida and Soltau (2022) used the film Interstellar (Nolan, 2014) to address modern physics in high school, using the power of movie scenes to capture students' attention, promote engagement, and facilitate the visualization of phenomena. Such cultural artifacts can broaden students' cognitive capacities and facilitate their understanding of GR.

Moura and Vianna (2019) began with a diagnosis of students' prior knowledge identifying difficulties with GR and Modern Physics concepts and feelings of incapability to comprehend them.

The film was used alongside conceptual discussions, to address the topics from a new perspective, promoting students' confidence and engagement to learn Physics.

Some remarkable scenes, such as the Miller's planet mission that illustrates gravitational time dilation, were the primary focus of the discussions. While this scene provides a helpful yet complex external processing, it may lead to the misconception that relativistic effects happen only in 'outer space' (de Souza et al., 2025).

From another perspective, Almeida and Soltau (2022) employed the flipped classroom methodology, with students first watching Interstellar to motivate participation and generate initial questions. Subsequent classes focused on discussions, exercises and experiments. Finally, students created videos or posters explaining the topics discussed and linked them to the movie scenes.

By interacting with the movie, selected YouTube videos, texts and producing their own videos and posters, students engaged with different cultural external resources to aid their comprehension of the theory, facilitating their information processing. The use of cultural artefacts as external processing tools can expand students' cognitive capacities (Souza et al., 2012). Films, being readily available and well-received by students, can stimulate curiosity and make GR more accessible when they draw upon familiar cultural experiences.

Science-art Festival

Grimberg et al. (2019) used a science-art festival to promote scientific engagement, merging physics, dance, and music for both students and general audience about gravitational waves and black holes. Collaborating with physicists and choreographers, a danced lecture choreography was produced inspired by the TED Talk Dance vs. Powerpoint a modest proposal (Bohannon, 2011) The dancers' movements, sounds echoing and the narrator words, artistically represented and explained the ripples in spacetime. A live interview with a physicists followed the danced lecture. Pre-test and post-test surveys and interviews revealed that participants' knowledge and interest in GR increased, and that many previously had a limited view of science, that was slightly developed after the festival.

Famous Paintings

Guerra et al. (2007) developed a sequence of activities connecting GR with famous artistic paintings. Working in groups, high school students analysed paintings identifying patterns of representations used and comparing them with the accepted scientific theories of that time. For example, in Picasso's Les Demoiselles d'Avignon, they identified revolutionary conceptions about time and changes in ideas of space perception. Then they discussed the influence of Relativity Theory on this change of the conceptions of space and time.

Subsequently, students organized the relationships between GR concepts and the historical and cultural context, presenting their findings creatively through plays, videos, or poetry. The authors highlighted students' great interest during the activities and the challenges posited by students' previous commonsense conceptions.

Using specifically identified art, such as Picasso's work, provides students with cultural external resources that can aid their comprehension of the main concepts of GR. Representing GR artistically and observing its influence on 20th century cultural development can establish connections that foster and broaden the information processing of students' brains (Souza et al., 2012).

Hypercultural Mediation

The hypercultural mediation happens by the interaction with digital tools used to perform programmed and logical actions, for example, by using virtual environments or computer simulations.

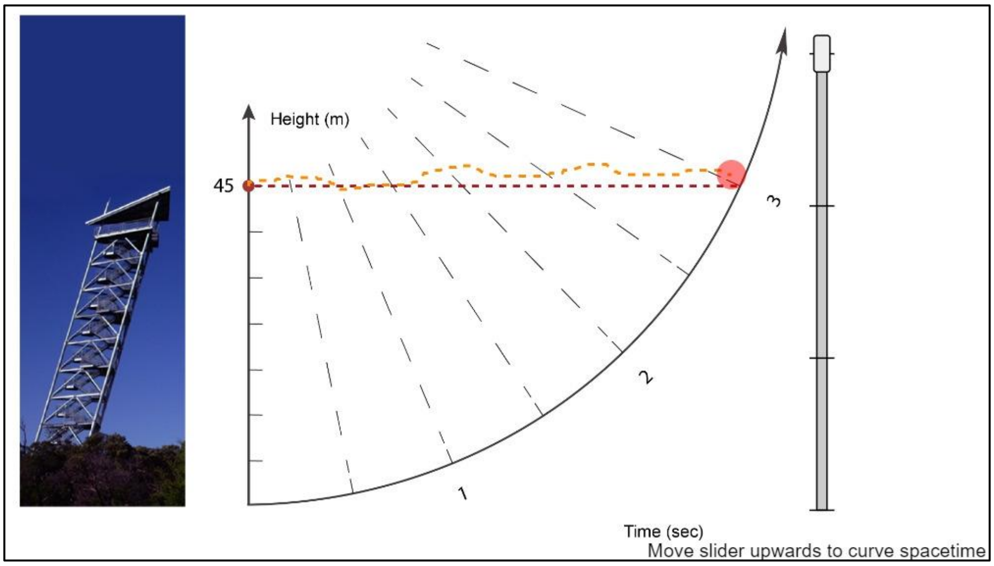
GR Virtual Environment

Machado and Santos (2004) developed and evaluated a course about gravitation where high school students could explore the environment by accessing available computer links. The authors noted that students struggled to solve the proposed problems involving calculations. Although this specific resource is now outdated due to technological advancements over the past two decades, the study reported the early use of hypercultural mediation for GR.

Nowadays, the hypercultural mediation for addressing GR is widely used. The ReleQuant virtual environment, which was presented and explained in various works of the research group (Henriksen et al., 2014; Kersting, 2019; Kersting et al., 2018; Kersting et al., 2020) includes a freely accessible virtual model constructed in the relativistic perspective of Newton's first law, referred to as 'Einstein's first law': 'objects free from the influence of forces move along geodesics in spacetime' (Kersting 2019, 2). The model represents free-fall in a diagram where time curves, according to Einstein's interpretation of gravity (Figure 7).

Figure 7

Time-distortion model where students should draw the trajectory of a free-falling object in a curved spacetime



Note. Kersting (2019).

The authors presented the model's functionalities and how it can complement the rubber-sheet analogy, where time is not represented. Kersting (2019) emphasized that the material was used by high school students, but some learning difficulties were still evident, such as time dilation visualization and conflicts between Newtonian and Einsteinian conceptions. Therefore, the author highlights the importance of using different resources that complement each other to overcome learning gaps.

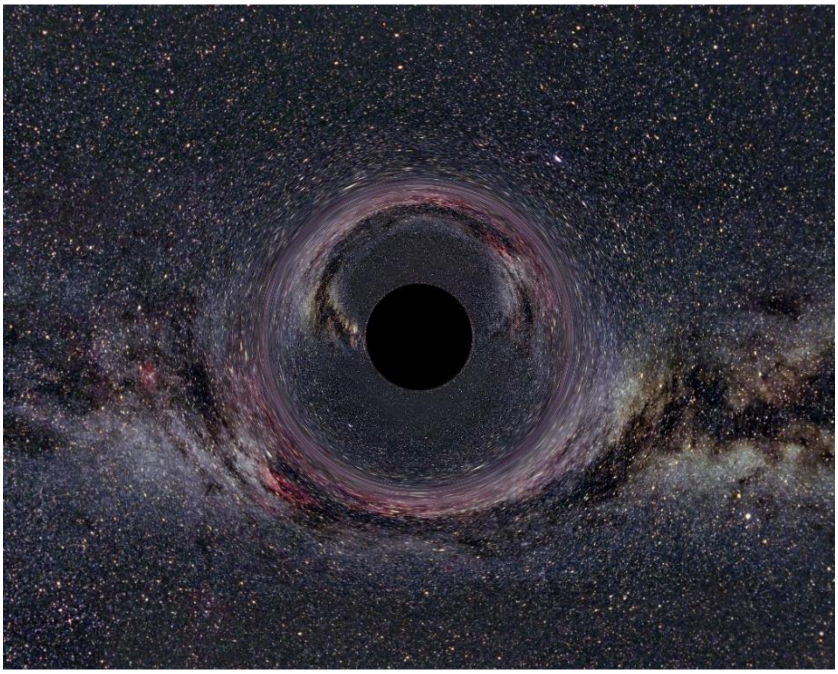
This interactive diagram allows for external information processing by visualizing time distortion caused by gravity. By interacting with this resource, students can broaden their cognitive capacity. The model is simple and freely accessible online (Kersting, n.d.), making it an excellent hypercultural tool (Souza et al., 2012) for teaching GR.

Computer Simulations

Kraus (2008) presented first-person simulations for both Special and General Relativity to facilitate students' visualization of relativistic effects. The GR simulation consists of visualizing a black hole's surroundings and observe the deflection of light. In this simulation, a black hole was positioned in front of the Milky Way, and the deflection of light emitted by the galaxy behind the black hole can be perceived as the observer approaches the black hole (Figure 8). Kraus (2008) discussed the use of these visualizations in exhibitions at German schools and proposed their use in secondary school physics education.

Figure 8

Simulation of a black hole of ten solar masses at 600 km



Note. Kraus (2008).

The simulation, freely available online (Kraus & Zahn, 2015), constitutes an interesting hypercultural tool that facilitates the visualization of light deflection, a phenomenon not observable in students' everyday life. Considering students' difficulties to imagine visual observations in the surroundings of extremely massive bodies, the simulation serves as an external resource for information processing, helping students better comprehend relativistic phenomena expanding their cognitive capacities (Souza et al., 2012).

More recently, Ferreira et al. (2021) reported using the interactive computer simulation Universe Sandbox to demonstrate collisions between two stars of equal masses, and two with different masses; and then between five stars, one massive central and four smaller stars at different distances. They also used the simulation to discuss the stars' velocity during the collision processes. Universe Sandbox is an interesting educational tool to visualize gravity effects in different situations helping students' information processing about the gravitational behaviour of different objects (Souza et al., 2012).

However, even though this is an interesting resource, using the Universe Sandbox requires purchasing a license, limiting its accessibility, particularly for many public schools. Moreover, it is important to consider the contradictions between students' everyday experiences and relativity concepts during the activities, such as the idea of 'gravity as a force' (Steier & Kersting, 2019), to achieve the expected outcome in GR understanding.

The computer simulations presented can be used with students through direct or indirect interaction. Direct interaction involves students manipulating the simulations in small groups using a computer under the teacher's guidance. Alternatively, indirect interaction is enabled by the teacher manipulating and demonstrating the simulations using a media projector.

Video-analysis Software

Marzari et al. (2023) reported activities developed using video recording and the software Tracker to investigate the Principle of Relativity and the Principle of Equivalence in classical mechanics taught in high school. These principles are crucial for understanding GR and the activities can be used to introduce them, even with a classical focus.

The students used Tracker to analyse videos of moving objects, for example, someone throwing balls and observing their trajectories from different reference frames. Marzari et al. (2023) also used cases with non-inertial reference frames, for example, an experimental car in an accelerated motion throwing a ball upwards. Addressing these principles in a classic view before introducing Relativity Theory is a good way to develop students' abilities to work with reference frame changes, a common difficulty among them (Di Casola, Liberati, and Sonegoc 2015).

The resources used are freely available online (Brown, Hanson, & Christian, 2025), making them accessible tools for different contexts. The videos and their analysis with Tracker can help students develop their information processing skills because the software can highlight different views of the movements that students may not perceive on their own. Moreover, using videos produced by students, such as throwing a ball, it is also possible to make a connection with the psychophysical mediation.

Sophotechnic Mediation

With the advent of Generative Artificial Intelligence (GenAI) in 2023, its usage in educational settings started to be explored. However, as a novel approach, no papers proposing activities using these resources for GR teaching were found. Considering the huge impact that the interaction with these new tools can cause in cognition, the Cognitive Networks Mediation Theory was recently updated to include Sophotechnic mediation (Souza et al., 2024). As a complete new set of competences are required to interact with GenAI, there is the possibility of relevant structural changes in individuals' cognition due to direct interaction with these tools.

Therefore, from the CNMT perspective, it becomes a new form of external cognitive mediation, due to its distinctive operational possibilities. According to Souza et al. (2024), the Sophotechnic mechanisms have 'the capacity to process natural-language queries so as to translate them into commands . . . producing desired content outputs' (p. 9). Considering this premise, we have already developed some activities using two different GenAI tools to approach GR. These activities are discussed below.

ChatPDF

This chatbot uses the Large Language Model (LLM) GPT 3.5 where it is possible to upload PDF files. The AI reads the files, and it is possible to ask questions about the document interacting with the GenAI. This tool is available online and can be freely accessed. Working with the main confirmations of GR (de Souza et al., unpublished), the students were divided into small groups with specific topics: Mercury perihelion precession, Sobral eclipse (1919), GPS, Large Hadron Collider, LIGO's first detection of gravitational waves, and first pictures of black holes (2019 and 2022).

Each group received a scientific communication paper about their topic and were instructed to upload it into ChatPDF. The students interacted with the GenAI asking questions about the topic of the paper uploaded. The objective was that the students became familiar with that specific confirmation of GR. The data collected with this activity was already analysed and will be included in a future paper.

When interacting with ChatPDF, students can ask specific questions concerning their doubts and obtain immediate answers. Therefore, this tool acts as an external resource helping students' brains process information. However, the quality of the outputs obtained depends on the quality of the inputs, that is, the quality of the prompts. In this sense, it is important to highlight that the students presented some difficulties to elaborate the questions about the papers' subjects to insert in the chatbot. Hence, students need to generate good prompts and interact efficiently with the GenAI (Souza et al., 2024).

AI Image-generator

Interesting tools that can help students communicate their understanding of scientific topics are the AI image-generators. In this context, we developed an activity using the BingAI image-generator. The students were instructed to think about what they imagine for the word 'relativity' and then describe this image to the AI generate it (de Souza et al., 2024).

This activity occurred before and after classes that consisted of learning about GR. The details of the activity and the main results are discussed in de Souza et al. (2024). This GenAI tool can help students to represent their mental imagery in a way different to traditional representations, like diagrammatic sketches. Moreover, the visualization of the results obtained from the AI can help students grasp the concepts and even enable them to perceive their own limitations on images which they have generated.

Therefore, the GenAI acts as an external agent performing tasks and helping the information processing in students' brains. Nonetheless, as well as with ChatPDF, the output obtained, that is, the image generated, depends on the prompt's quality. Some students analysed their difficulties in externalizing what they imagined: other students even presented their thoughts that showed their difficulties in forming clear mental images related to 'relativity'. Based on this study, it is very clear that students need the ability to translate their mental imagery process into prompts using natural language.

Discussion

From the analysis of selected studies, we identified the availability of varied materials and accessible resources for use in the classroom. These studies used simulations and software, analogies with experimental construction, films, and interactive activities among students, thus covering the five mediation levels of CMNT (Table 3). These resources can be used in different social contexts because many of them can be adapted to different situations.

Evidently, some educational technologies presented a higher potential to promote external processing of information than did others. Among them, we highlighted the approaches of GR topics that are crucial to its understanding and with which students usually struggle. These external resources can expand students' cognitive capacities (Souza et al., 2012).

As spacetime curvature is one of the main concepts of GR (McInerney & Sutton, 2024), the psychophysical resources of the rubber-sheet model (Postiglione & De Angelis, 2021a) and the sector models (Zahn & Kraus, 2014) are interactive tools that enable students to visualize this curvature, even with the limitations already presented. The resources are easily accessible and, besides providing external processing of information, they also promote social interactions among students.

The use of the movie Interstellar is also a powerful tool. As many students are familiar with the movie, it can promote their engagement in the learning process (Moura & Vianna, 2019). The scene of the Miller's planet mission, about gravitational time dilation, provides a helpful external processing. As students struggle to understand this phenomenon as real, due to the conflict with everyday experiences (Kraus, 2008), watching the scene and seeing time dilation effects can help them in information processing.

Also dealing with time dilation, the ReleQuant virtual environment has potential to promote external processing (Kersting, 2019). This resource can complement the rubber-sheet model providing the visualization of warped time. Moreover, it is an interactive tool freely available online. As the resource involves free-fall it can be used combined with the graphical representations presented

(Stannard, 2018), enriching the mediation process. This approach might help to integrate the Einsteinian interpretation of free-fall to students' previous conceptual domains, which often become a challenge for their understanding (Bandyopadhyay & Kumar, 2010).

Dealing with the Equivalence Principle, the seatbelt analogy can be easily used and provides powerful insights for students in their learning process (Oliveira et al., 2019). Moreover, the free-fall experiments also can be effective tools to teach this principle (Boublil et al., 2023). As students have difficulties with reference frame changes, they face challenges understanding the meaning of these changes (Gousopoulos et al., 2015). Therefore, using the experiments described in this review paper it is possible to promote external information processing, thereby helping overcome these difficulties.

Finally, we highlight GenAI tools and proposed activities described here using them. The use of the GenAI in the educational setting only started recently but already shows promising potential. Even though we could not find any reports of its use in the classroom, we expect the number of works using GenAI tools to increase soon.

Table 3

Synthesis about the educational technology used in the reviewed studies

Mediation	Resource	Year Level	Researchers	Activity and GR Concepts	Common difficulties
Psychophysical	Sector models	High school	Zahn and Kraus 2014, 2019; Kraus and Zahn 2019	Extrinsic visualisation of curved 3D space using cardboard blocks	Idea of 2D curvature
	Rubber-sheet model	Elementary to high school	Baldy 2007; Kaur et al. 2017; Ruggiero et al. 2021; Postiglione and De Angelis 2021a, b	Understanding that a large mass distorts spacetime and influence the movement of other bodies using a Lycra sheet and different size spheres	Gravity has a downward pull; 2D curvature only on space
	Falling objects	Elementary to high school	Boublil et al. 2023	Recognising that free fall is equivalent to an inertial reference frame using falling objects, such as leaking cup of water	Reference frame changes; ideas of an absolute reference frame
	Metallic globe	High school; Lower undergraduate	*Andersen 2020	Measurements on the globe's curved surface show need for non-Euclidean geometry	Everyday flat space conceptions
	Water swirling vortices	High school	*Barr et al. 2016	Shadows in vortexes of water simulate behaviour of light around black holes	Visual metaphor, not the explanation for light bending
	Seatbelts	Elementary to high school	*Oliviera et al. 2016	Comparing inertia principle to gravitational field effects to explain the Equivalence Principle	Reference frame changes to understand 'inertia as a local gravity'
	Wineglass base	High school	*Huwe & Field 2015	Laser projection in wineglass base simulates visualisation of gravitational lensing	Visual metaphor, not the explanation for gravitational lensing
	Experimental solar eclipses data	High school	*Goldoni and Stefanini 2020	Light deflection measurements in eclipses used to compare Newtonian and Einsteinian theories	Small deflections measured to use for calculating
Social	Conceptual group discussions	High school	Kersting and Steier 2018; Steier and Kersting 2019	Discussions in pairs about the rubber sheet analogy to explain gravity and free-fall	Imagination and expression of ideas; imperceptibility if GR effects in everyday life
Cultural	Science movies	High school	Moura and Vianna 2019; *Almeida and Soltau 2022	Use of *Interstellar* movie to illustrate GR effects and engage students	Idea that relativistic effects happen only at 'outer space'; students feel incapable to comprehend GR concepts
	Science-art festival	Elementary to high school	Grimberg et al. 2019	'Celebrate Einstein Festival' with danced lecture representing black holes and	Previous limited view of science

				gravitational waves, and interviews with physicists	
	Famous paintings interpretations	High school	Guerra et al. 2007	Analysis of the relativity influence in the representation of space and time on paintings	Previous commonsense conceptions
Hypercultural	GR virtual environment	High school	Machado and Santos 2004	Courseware about gravitation where students can explore and access available links	Struggle to solve proposed problems involving calculus
		High school	Henriksen et al. 2014; Kersting et al. 2018; Kersting 2019; Kersting et al. 2020	Virtual environment addressing GR topics where students can interact and access different resources, such as the 'time distortion model'	Difficulty in visualization of gravitational time dilation; conflict of Newtonian and Einsteinian conceptions
	Visual graphic diagrams	High school	*Stannard 2018; *Stannard et al. 2017	Graphic diagrams representing free-fall using Einsteinian interpretation	Difficulty in visualization of gravitational time dilation; difficulty to interpret free-fall in Einsteinian view
	Computer simulations	High school	Kraus 2008	First-person visualization of a black hole in front of Milky Way showing light deflection	Difficulty in imagine visual observations in high-gravity surroundings
		High school	Ferreira et al. 2021	'Universe Sandbox' simulation of stars' collision	Ideas of gravity as a 'force'; contradiction between everyday experiences and relativity
	Video-analysis software	High school; Undergraduate	Marzari et al. 2023	Use of 'Tracker' software to analyse videos of inertial and non-inertial movements and address Relativity Principle and Equivalence Principle	Difficulty in analysing movement from different reference frames
Sophotechnic	ChatPDF	High school	de Souza et al. not published	Upload on ChatPDF of science communication papers about relativity corroborations, asking questions and elaborating posters	Limited interaction with the chat and difficulty to elaborate questions regarding the papers
	AI-image generator	High school	de Souza et al. 2024	Use of Bing AI image generator to create images that represents what students imagine for 'relativity'	Difficulty in forming clear images related to 'relativity'; difficulty in externalising what was imagined

Note. *Without reporting the test of the resource, some of these findings are from other papers dealing with the same topic but not necessarily the same resource

Conclusion

The concept of General Relativity uses an interpretation of nature that contradicts common-sense. Consequently, GR involves highly abstract and hardly perceptible concepts in everyday life, creating great difficulties in the imaginative process of the phenomena involved (Steier & Kersting, 2019). Therefore, the importance of using different mediations and educational technologies that allow such visualization to occur is highlighted, contributing to an understanding of GR.

Using the background of the Cognitive Mediation Networks Theory (Souza et al., 2012; Souza et al., 2024) we presented a literature review aiming to identify these available educational technology resources. Through the research conducted, it was possible to find a range of different resources using the five external mediation levels of CMNT. Many of these resources have great potential to be used in GR teaching because they are developed with easily accessible materials that teachers can use with their students.

Through the results obtained it was possible to answer the three initial research questions. For each work selected, the target level of instruction was identified, answering the Q1. Moreover, each educational resource identified was classified according to the different mediation levels, answering the Q2. Finally, we discussed how these educational resources might help students to overcome the main difficulties reported in the literature, answering Q3. These results answering the research questions were summarized in Table 3.

We acknowledge the limitations of this systematic literature review that should be considered when interpreting the results. Firstly, the search strategy was limited to sources indexed in the databases used (ERIC, Scopus, SciELO and Google Scholar). Therefore, some eligible studies may not have been included in our analysis. Moreover, the eligibility criteria and search strategy focusing specifically on resources for teaching General Relativity may have led to the omission of some relevant studies exploring educational technologies for other complex physics topics that could potentially be adapted for GR.

The quality and risk of bias of the included studies was not formally assessed, as some of them described proposed teaching resources without robust empirical testing. Considering the studies that did test the presented resources, most did so in a limited educational context, so the generalizability of the results to other student populations is unknown. More rigorous empirical studies across diverse contexts are needed to establish the efficacy of the identified resources for supporting student understanding. However, the present review aims to present potential educational technologies to be used, and not to evaluate their effectiveness.

Despite the limitations mentioned above, this review provides a valuable synthesis of available resources leveraging different external mediation levels and highlights promising tools and strategies that can serve as a starting point for educators seeking to incorporate these topics into physics curricula. Considering the limited number of empirical studies that we identified from 2000 to 2024, the findings also underscore the need for further research to develop evidence-based recommendations for the optimal use and combination of educational technologies to teach General Relativity and other challenging scientific theories.

The identified gaps, such as the lack of fully validated instructional tools or insufficient alignment with systematic curricular standards, suggest opportunities for future studies to integrate robust assessment frameworks and cross-cultural comparisons. By mapping the identified resources on to theoretical perspectives, we highlight not only their instructional potential but also the need for evidence-based refinement and rigorous empirical testing

As Modern and Contemporary Physics topics are, up until recent times, rarely present in the school environment (Kaur et al., 2017), we anticipate that this review will facilitate the use of and accessibility to educational technology resources for teachers, thereby encouraging the teaching of GR and assessments of students' learning. Finally, this analysis to identify available resources for teaching GR can be replicated for all other teaching fields, not only science education. This strategy can also be used to identify assistive technology for inclusive education using the external mediations (Picanço et al., 2022). The approach described in this paper, guided by the CMNT, can help the teaching of complex concepts that rely heavily on information-processing, knowledge acquisition, abstraction, and other cognitive mechanisms.

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Declaration of interest

The authors have no competing interests to declare that are relevant to the content of this article.

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