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Electromagnetic radiation: A comprehensive review of misconceptions

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ABSTRACT

Electromagnetic radiation (EMR) is integral to both the natural world and technological innovation, yet widespread misconceptions about its nature and effects persist among the public, educators, and students. This comprehensive review examines these misconceptions, analyzing their origins–including inadequate education, the complexity of EMR concepts, media misrepresentation, and educators' own misunderstandings–and their impact on scientific literacy and public health. By reviewing a wide range of scientific studies, we identify common misunderstandings, such as conflating ionizing and non-ionizing radiation, believing all radiation is harmful, and confusing irradiation with contamination. These misconceptions contribute to unwarranted health anxieties, resistance to beneficial technologies, and challenges in science education. We highlight the critical need for effective EMR education through curriculum integration, innovative teaching methods, and enhanced teacher training. By addressing these misconceptions through strategic educational reforms and evidence-based communication, we aim to foster a scientifically literate society capable of making informed decisions about EMR and its applications.

Keywords: electromagnetic radiation, misconceptions, non-ionizing radiation, science education, physics education

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INTRODUCTION

Electromagnetic radiation (EMR) is a fundamental component of the physical universe, spanning a spectrum of energy forms that are vital to both natural phenomena and technological advancements (Batool et al., 2019; Jagetia, 2022; Wang et al., 2014; Yin et al., 2022; Zwinkels, 2014). EMR profoundly influences our daily lives, from the warmth provided by sunlight to the capabilities of medical imaging devices (Hewitt, 2015). Despite its importance and pervasiveness, the general public frequently has a poor understanding of EMR, which results in many misunderstandings. These misconceptions can have serious consequences, such as unjustified health concerns, opposition to new technology, and difficulties in teaching science (Gavrilas et al., 2022b; Laitinen et al., 2014; Tsai et al., 2020; World Health Organization [WHO], 2014).

Misconceptions about EMR are not confined to the general public; they are also prevalent among educators, high school students, and university students. This lack of accurate understanding directly impacts learning outcomes and future teaching practices (Neumann & Hopf, 2013). Students may have major misconceptions regarding the nature of radiation, its sources, and its consequences on health, which can perpetuate scientific illiteracy and obstruct effective physics education (Gavrilas & Kotsis, 2023a; Kotsis, 2024). Concerns about the possible health consequences of EMR exposure, particularly from mobile phones and wireless networks, have sparked public discussion and alarm (Farashi et al., 2022; International Agency for Research on Cancer [IARC], 2011). University students and young adults are especially heavy users of mobile phones, making them a key demographic for studying the impact of EMR misconceptions. Integrating EMR education into school curricula and utilizing engaging teaching methods, such as conceptual change texts and interactive activities, have shown promise in enhancing student understanding (Boyes & Stanisstreet, 1994; Henriksen & Jorde, 2001; Kotsis, 2024; Mubeen et al., 2008; Plötz, 2017). By employing these approaches, educators aim to capture students' interest, correct misunderstandings, and foster scientific literacy.

This review comprehensively examines misconceptions about EMR, drawing upon a wide range of scientific studies. We aim to identify common misconceptions, analyze their origins, examine recent research on health concerns related to EMR, highlight the importance of effective EMR education, and propose strategies to address them.

OVERVIEW OF THE ELECTROMAGNETIC SPECTRUM

The electromagnetic spectrum is a foundational concept in physics that encompasses the complete range of EMR types, each distinguished by specific wavelengths and frequencies. This spectrum includes a diverse array of radiation forms, from low-frequency radio waves to high-frequency gamma rays (Abdo et al., 2007; Felder & Felder, 2022; Feynman et al., 2007). Grasping the electromagnetic spectrum is essential for understanding how different types of EMR interact with matter and affect biological systems. Moreover, it plays a critical role in numerous technological and medical applications, making it a cornerstone of scientific literacy and public awareness (Kotsis, 2024).

The electromagnetic spectrum is traditionally divided into sections based on wavelength and frequency, with each zone representing a certain type of radiation (Felder & Felder, 2022). These regions, radio waves, microwaves, infrared (IR) radiation, visible light, ultraviolet (UV) radiation, X-rays, and gamma rays, cover the entire spectrum of electromagnetic phenomena (Geisler et al., 2021; Hewitt, 2015; IARC Working Group on the Evaluation of Carcinogenic Risks to Humans, 2012; Kawase et al., 2015). Each form of EMR has distinct properties and interacts with matter in various ways, determining its uses and effects on living creatures (Grimes, 2022).

Radio waves, occupying the longest wavelengths and lowest frequencies in the electromagnetic spectrum, are primarily utilized in communication technologies such as television, radio broadcasting, and mobile phone networks (Bartz, 2017; Ugweje, 2004). Microwaves, with slightly shorter wavelengths than radio waves, find applications in radar technology and microwave ovens (Goiceanu et al., 2011; Merckel, 1972; Osepchuk, 2009). IR radiation, perceived by humans as heat, is essential in applications like thermal imaging and remote sensing (Kuenzer & Dech, 2013; Neinavaz et al., 2021).

The human eye can detect only visible light, which ranges from red (longer wavelengths) to violet (shorter wavelengths). This portion of the spectrum is critical for vision and a variety of technical uses, including photography and fiber optic transmission (Ergul et al., 2015; Narla et al., 2020). UV radiation, which has shorter wavelengths than visible light, can trigger chemical reactions such as sunburn. It is also employed in sterilizing procedures and vitamin D generation in the skin (Gromkowska-Kępka et al., 2021; Matsumura & Ananthaswamy, 2004; Meyer & Stockfleth, 2021; Østerlind, 1993; Saric-Bosanac et al., 2019; Tang et al., 2024).

X-rays and gamma rays occupy the high-frequency end of the spectrum and have enough energy to penetrate most materials, which makes them invaluable in medical imaging and cancer treatment. However, their high energy levels also pose risks, as they can ionize atoms and damage biological tissues (Bell et al., 2022; Hill, 2004; Hussein et al., 2021; Poirier et al., 2020; Rahman et al., 2018; Yamamoto et al., 2023).

IONIZING VS. NON-IONIZING RADIATION

One of the most critical distinctions within the electromagnetic spectrum is between ionizing and non-ionizing radiation. This distinction is based on the energy level of the radiation and its ability to ionize atoms, which has significant implications for its biological effects and health risks (Azzam et al., 2012; Havránková, 2020; Mehdipour et al., 2021; Talapko et al., 2024; Xiao et al., 2020).

Ionizing radiation includes X-rays, gamma rays, and high-energy UV radiation. It has enough energy to remove bound electrons from atoms, known as ionization (Bagatin & Gerardin, 2020; Liu et al., 2021; Reeve, 2018; Shayanfar & Pillai, 2022). This capability allows ionizing radiation to cause molecular damage, particularly to DNA, which can result in mutations and increase the risk of cancer (Maayah et al., 2022; Miousse et al., 2017; Sasanuma et al., 2020; Sitmukhambetov et al., 2023). The biological impact of ionizing radiation depends on several factors, including the dose, duration of exposure, and the specific type of radiation. For example, while a medical X-ray delivers a controlled dose of ionizing radiation that is generally considered safe, prolonged exposure to high levels of gamma radiation, such as from radioactive materials, can be hazardous (Choppin et al., 2013).

Non-ionizing radiation encompasses radio waves, microwaves, IR radiation, visible light, and lower-energy UV radiation. Unlike ionizing radiation, it lacks sufficient energy to ionize atoms or molecules. Instead, non-ionizing radiation causes molecules to vibrate or rotate, leading to thermal effects (Bryan, 2001; Wood & Karipidis, 2017). Microwaves heat food by inducing vibrations in water molecules, which generates heat (Deng et al., 2022; Heddleson & Doores, 1994; Vollmer, 2004). IR radiation is perceived as warmth by humans, and visible light allows us to see the world around us (Prangnell, 2016; Rizzi & Bonanomi, 2012; Wang & Zhao, 2022).

Understanding the distinction between ionizing and non-ionizing radiation is crucial for accurately assessing the health risks associated with various forms of EMR exposure. Ionizing radiation can lead to severe biological damage at high doses (Mehdipour et al., 2021; Xiao et al., 2020), whereas the effects of non-ionizing radiation are generally limited to thermal impacts (Belpomme et al., 2018; Lahir, 2023; Tuieng et al., 2021). This differentiation is essential in fields ranging from radiation safety and public health to educational initiatives aimed at dispelling common misconceptions about EMR.

BIOLOGICAL INTERACTIONS OF ELECTROMAGNETIC RADIATION

How EMR interacts with biological systems depends on its energy and the type of tissue it encounters. Due to its high energy, Ionizing radiation can break chemical bonds and damage cellular structures, particularly DNA (Borrego-Soto et al., 2015; Jia et al., 2021; Reisz et al., 2014). This damage can lead to mutations, potentially resulting in cancer or other health problems. Ionizing radiation is both a valuable tool in medicine and a potential health hazard (Mladenova et al., 2022; Talapko et al., 2024). It is used in medical imaging technologies like X-rays and computed tomography scans to visualize the body's internal structure and in radiation therapy to target and destroy cancerous cells (Pereira et al., 2014; Vila et al., 2010). However, strict safety protocols are necessary to minimize exposure and protect patients and healthcare workers (Heston & Tafti, 2024; McGowan et al., 2023).

Non-ionizing radiation, on the other hand, typically interacts with biological tissues in less harmful ways. Radio waves are used in magnetic resonance imaging to create detailed images of internal organs (Carr & Grey, 2002; Edvardsen & Rosen, 2005; Lamb & Gedroyc, 1997). Visible light, crucial for vision, also plays a role in processes like photosynthesis in plants and vitamin D synthesis in the human body (Aiello et al., 2024; Gudkov et al., 2017; Kochetova et al., 2022). While non-ionizing radiation is generally considered safe, excessive exposure to certain types, such as UV light, can cause damage. Overexposure to UV radiation can lead to skin damage and increase the risk of skin cancer (D'Orazio et al., 2013; Ichihashi et al., 2003).

TECHNOLOGICAL AND MEDICAL APPLICATIONS OF THE ELECTROMAGNETIC SPECTRUM

The electromagnetic spectrum is integral to numerous technological and medical applications, which rely on different types of EMR to function. Radio waves are essential for wireless communication, enabling technologies like mobile phones, Wi-Fi, and GPS (Daher et al., 1994; Idris et al., 2014; Yan, 2024; Zeleke et al., 2021). These applications depend on the ability of radio waves to travel long distances and penetrate buildings, making them ideal for transmitting information over large areas (Doviak & Zrnić, 1993; Frenzel, 2010; Sinclair, 2011).

Microwaves are used in household appliances like microwave ovens, radar systems, and satellite communication (Amoah et al., 2018; Karmakar, 2016; Lacomme et al., 2001). The ability of microwaves to penetrate fog and clouds makes them particularly useful in navigation and meteorology (Carassa, 1973; Junying & Yongli, 2019; Thi Phuoc Van et al., 2019). IR radiation has applications in night vision equipment, remote controls, and thermal imaging, allowing us to see heat patterns in the environment and even detect diseases based on body temperature variations (Bramson, 1968; Puneet et al., 2022; Qu et al., 2015; Yan et al., 2021).

Visible light, in addition to its obvious role in illumination and vision, is used in various optical technologies, including cameras, microscopes, and fiber optics. Manipulating visible light through lenses and mirrors enables us to explore the microscopic world and transmit information through light signals over vast distances (Ergul et al., 2015; Narla et al., 2020).

While harmful in large doses, UV radiation is harnessed for beneficial purposes such as sterilizing medical equipment and purifying water. It is also crucial for producing vitamin D in the skin, which is essential for bone health (Gromkowska-Kępka et al., 2021; Matsumura & Ananthaswamy, 2004; Meyer & Stockfleth, 2021).

X-rays and gamma rays, due to their high energy and penetrating power, are invaluable in medical diagnostics and treatment (Johnson et al., 2022; Nallanthighal et al., 2016; Rodrigues & Singhal, 2024; Schmidt et al., 2022). X-rays are used to image bones and detect fractures (Rahman et al., 2018), while gamma rays are used in cancer treatment to destroy malignant cells with precision (Baskar et al., 2012; Mosayebnia et al., 2023).

THE NEED FOR ELECTROMAGNETIC RADIATION EDUCATION

Given the diverse and significant applications of the electromagnetic spectrum, education systems need to provide students with a thorough understanding of EMR and its properties. This knowledge is crucial for future scientists and engineers and informed citizens who can make decisions about technology and health (Ardito et al., 2021; Gavrilas & Kotsis, 2023b; Han, 2020; OECD, 2005). Misconceptions about EMR, such as the belief that all radiation is harmful or that mobile phones emit dangerous levels of radiation, are widespread and can lead to public anxiety and resistance to technologies (Gavrilas & Kotsis, 2023b; Jauchern, 1991; Krawczyk et al., 2020; Neumann, 2014).

Educational strategies should emphasize the distinctions between different types of radiation, their interactions with matter, and their respective risks and benefits. Students should learn about the safety of everyday non-ionizing radiation exposure from devices like microwaves and mobile phones, as well as the precautions necessary when dealing with ionizing radiation in medical settings (Furuta & Kusama, 2014; Millar, 1994; Millar et al., 1990; Prokop & Nawrodt, 2024; Schuette et al., 2023; Silva & Trindade, 2022; Singh et al., 2008; Wojcik et al., 2019).

Furthermore, public outreach and communication are vital for addressing misconceptions and promoting scientific literacy (Directorate-General for Internal Policies of the Union (European Parliament) et al., 2019; Lopes et al., 2024; OECD, 2023; Tuttle et al., 2023; Valladares, 2021). Accurate information from trusted sources can help dispel myths and ensure that the public understands the benefits and limitations of technologies that rely on EMR. Understanding the properties and interactions of different types of EMRs is essential for assessing their risks and benefits and making informed decisions about their use. By improving education and public awareness of the electromagnetic spectrum, we can foster a more scientifically literate society capable of navigating the challenges and opportunities of a technologically advanced world.

MISCONCEPTIONS IN PHYSICS EDUCATION AND THEIR IMPACT ON SCIENTIFIC LITERACY

Misconceptions about EMR are widespread and can significantly impede the development of scientific literacy. These misunderstandings often originate from inadequate educational curricula, the complex nature of the subject, and misinformation spread through media and popular culture (Gavrilas et al., 2022a; Kotsis, 2024; Neumann, 2014; Rowley & Mazar, 2021). Such misconceptions can lead to confusion and reinforce incorrect beliefs, persisting into adulthood and influencing public perception of science and technology. Understanding the roots of these misconceptions and addressing them effectively within the educational system is crucial for fostering a scientifically literate society (Bórquez-Sánchez, 2024; Douglas, 2007; Kotsis & Stylos, 2023; Mandinach & Schildkamp, 2021; Panagou et al., 2024; Shortland, 1988; Tuttle et al., 2023).

Origins of Misconceptions

Misconceptions about EMR can arise from several factors, including gaps in education, the inherent complexity of the subject, misinformation from media sources, and even teachers' misunderstandings. These factors contribute to the persistence and proliferation of incorrect beliefs about EMR (Gavrilas et al., 2022a; Kotsis, 2023).

Inadequate Education

One of the primary sources of misconceptions about EMR is the inadequate coverage of the topic in educational curricula. High school physics courses often focus on traditional mechanics and thermodynamics, with EMR receiving only cursory treatment (Gavrilas & Kotsis, 2023a). This limited exposure leaves students with a fragmented understanding of EMR concepts, such as the electromagnetic spectrum, the differences between ionizing and non-ionizing radiation, and the principles governing the interaction of EMR with matter. Highlight that many curricula fail to provide a coherent framework that connects these concepts, resulting in students who can memorize definitions but struggle to apply them in real-world contexts (Kotsis, 2024; Plotz, 2017).

Furthermore, the sporadic treatment of EMR across different grade levels can confuse students, who might encounter basic concepts in middle school and then not revisit them in detail until much later, if at all. This education gap prevents students from building a solid, integrated understanding of how EMR works and its various applications, from everyday technologies like microwaves and mobile phones to more specialized uses such as medical imaging and radiation therapy (Buschke, 1961; Formenti et al., 2016; Jauchem, 1995; Wolfe & Cognetta, 2016).

Complexity of the Subject Matter

The abstract nature of EMR and complex interactions with matter present another significant challenge for educators and students alike. Concepts such as wave-particle duality (Davydov, 2012; Dimitrova & Weis, 2008; Li et al., 2023), energy quantization (Dan & Mahapatra, 2009; Martino, 2023), and electromagnetic wave propagation (Bochner, 2021; Ishimaru, 2017; Sasiela, 1994; Shibata et al., 2017) are not only difficult to visualize but also require a higher level of abstract thinking. Understanding that light can exhibit wave-like and particle-like properties depending on context is challenging against everyday experiences. Similarly, the concept of energy quantization, where EMR is emitted or absorbed in discrete units called photons, can be difficult to grasp without a solid mathematical foundation. Without effective teaching methods, such as visual aids, simulations, and interactive experiments, students are likely to develop misconceptions (Kotsis, 2023). Addressing these misconceptions requires accurate information and pedagogical strategies that make these abstract concepts more accessible and relatable to students (Engelmann & Huntoon, 2011; Hoffer, 2019; Mandinach & Schildkamp, 2021).

Media Influence and Misinformation

Media portrayals of EMR often contribute to public misconceptions, sensationalizing its dangers or presenting distorted views of scientific facts. Popular culture frequently associates radiation with disaster, illness, and death, as seen in movies and TV shows that depict nuclear accidents, radiation-induced mutations, or the use of EMR as a weapon (Acar-Sesen & Ince, 2010; Gavrilas & Kotsis, 2023a; Houston et al., 2018; Morales-López & Tuzón-Marco, 2022; Vettenranta, 1996). Such portrayals can profoundly impact public perception, reinforcing the idea that all forms of radiation are harmful and should be feared.

Sensationalized news reports can also exacerbate these misconceptions. Media coverage emphasizing potential health risks associated with mobile phone use or Wi-Fi without providing a balanced scientific context can spread public fear. Media misrepresenting scientific findings contributes significantly to public misconceptions, particularly when complex topics are oversimplified or miscommunicated (Acar-Sesen & Ince, 2010; Gavrilas et al., 2022a; Houston et al., 2018). This is further complicated by the prevalence of misinformation online, where unverified sources and conspiracy theories can spread rapidly, reaching audiences that may lack the critical thinking skills necessary to assess the validity of the information presented (Aïmeur et al., 2023; Beauvais, 2022; Del Vicario et al., 2016; Gavrilas & Kotsis, 2024; Joseph et al., 2022; Luo et al., 2021; Muhammed & Mathew, 2022; Rodrigues et al., 2024).

Teachers' Misconceptions

Teachers themselves can sometimes be a source of misinformation if they hold incorrect beliefs about EMR. Without adequate training and resources, educators may struggle to convey accurate information and may unintentionally pass on their misconceptions to students (Kendeou & Johnson, 2024; Nygren et al., 2022; Siani et al., 2024; Zucker et al., 2020). Professional development programs that focus on both content knowledge and pedagogical strategies can help educators clarify their understanding and equip them to address student misconceptions more effectively (Darling-Hammond et al., 2024; Gavrilas et al., 2024c; Hyseni Duraku et al., 2022; Pozo-Rico et al., 2020; Ventista & Brown, 2023).

MISCONCEPTIONS ABOUT ELECTROMAGNETIC RADIATION

Misconceptions about EMR are widespread, particularly among students and educators. To address this issue, a comprehensive literature review was conducted to identify and analyze misconceptions related to EMR. A systematic search was performed across multiple scientific databases, including Google Scholar, PubMed, ScienceDirect, JSTOR, IEEE Xplore, arXiv, SpringerLink, Wiley Online Library, Scopus, and ERIC, using the specific keywords "misconceptions" and "electromagnetic radiation." This search aimed to locate peer-reviewed articles, conference proceedings, and educational resources that explore misunderstandings and incorrect beliefs held by various populations regarding EMR and its effects. The search strategy was designed to capture literature examining how misconceptions about EMR are formed, propagated, and addressed.

The retrieved articles were evaluated based on their relevance to misconceptions about EMR, particularly those related to safety, health impacts, and public understanding. The comprehensive search ensured a thorough overview of the topic by spanning scientific, technological, and educational disciplines. The following sections explore the most common misconceptions about EMR, supported by scientific evidence from various studies. **Table 1** summarizes studies examining misconceptions about radiation and their findings.

Common Misconceptions About Electromagnetic Radiation

One pervasive misconception is that all forms of radiation are inherently harmful and dangerous. Studies such as those by Morales López and Tuzón Marco (2022) and Neumann (2014) have found that many students and teachers associate radiation solely with danger, particularly linking it to nuclear energy and radioactive materials. This generalized fear overlooks the benign or beneficial forms of radiation, such as visible light and radio waves used in communication.

Table 1. Studies examining misconceptions about radiation

Study	Sample and size	Misconception about radiation	Type of radiation	Main findings
Balta (2018)	106 high school physics teachers in Turkey	Blackbody radiation is misunderstood as solely absorbing or emitting energy and is often confused with visible radiation.	Blackbody radiation (thermal radiation)	Teachers displayed incomplete knowledge of blackbody radiation, with misconceptions about its definition and behavior. Many thought a blackbody only absorbs or emits at certain wavelengths. Teaching strategies are needed to address gaps in understanding, especially about its relationship to temperature and emission across all wavelengths.
Bezen et al. (2021)	18 pre-service physics teachers in Turkey	Blackbody radiation only occurs at high temperatures and emits visible light.	Blackbody radiation (IR and visible)	Teachers had misconceptions about blackbody radiation, believing it occurs only at high temperatures. Knowledge gaps exist in understanding thermal radiation.
Boyes and Stanisstreet (1994)	1,365 pupils aged 11-16 from 42 groups in 14 schools	Radiation comes primarily from man-made sources (nuclear power), which is confused with environmental issues	Ionizing radiation (nuclear, X-rays, and gamma rays)	Students incorrectly associated radiation with nuclear power stations and global environmental issues like ozone depletion and global warming. They also misunderstood how radiation travels and its industrial and medical uses.
Buschke (1961)	Not explicitly stated, multiple clinical cases	Radiation therapy causes unavoidable radiation sickness	X-rays and super voltage radiation	Radiation sickness can be avoided with proper technique. Super voltage therapy significantly reduces risks.
Claassen et al. (2017)	245 participants in the Netherlands	EMF exposure is mainly from public sources, like base stations	RF radiation	Providing information about EMF exposure improves understanding, but personal exposure from mobile phones is underestimated.
Englander and Ghatan (2021)	Not applicable (review article)	Fluoroscopic-guided interventions (during pregnancy lead to infertility, miscarriage, or childhood cancer	Ionizing radiation (X-rays and gamma rays)	The study debunks myths regarding radiation exposure during pregnancy, showing that occupational radiation exposure for interventional radiologists is well below harmful levels. With proper safety measures, pregnant IRs can safely perform fluoroscopic procedures without increasing risks of infertility, miscarriage, or childhood cancer.
Formenti et al. (2016)	Not applicable (review)	Radiation therapy is immunosuppressive and always harmful	Ionizing radiation (X-rays and gamma rays)	Radiation therapy can have both immunosuppressive and immunogenic effects and complement immunotherapy in cancer treatment.
Gabovich and Gabovich (2007)	Not applicable (theoretical study)	Photons having zero mass implies that electromagnetic radiation has no mass	General EMR (light and photons)	Photons have zero rest mass, but confined electromagnetic radiation has non-zero mass. This misconception results from misunderstanding relativistic physics.
Gavrilas and Kotsiz (2023a)	427 pre-service teachers in Greece	Cell phones and Wi-Fi emit radioactivity	RF radiation	Most participants incorrectly believed that mobile phones and Wi-Fi networks emit radioactivity.
Gavrilas and Kotsis (2023b)	619 university students in Greece	Mobile phones emit harmful radiation that causes immediate health problems.	RF radiation	The study found that 87.6% of students reported at least one symptom after excessive phone use, such as headaches or pressure in the head. The perception that mobile phone use directly causes these symptoms is widespread, but no conclusive evidence connects these symptoms to radiation exposure.
Gavrilas et al. (2022a)	619 university students in Greece	Mobile phones and Wi-Fi networks emit harmful radioactivity	RF radiation	74.2% of students believed cell phones emit radioactivity, and only 32% correctly understood that Wi-Fi networks do not emit radioactivity. Students had misconceptions about the health risks of non-ionizing radiation from common devices.
Geisler et al. (2021)	Not applicable (review article)	Regular sunscreens protect against visible light	Visible light (400-700 nm)	Traditional sunscreens only protect against UV radiation. Visible light requires tinted sunscreens with iron oxides.
Gordon (1994)	Not applicable (review article)	Non-ionizing radiation, such as from power lines, is harmless	ELF and RF radiation	Growing concerns about the harmful effects of low-frequency non-ionizing radiation (from power lines and appliances) were explored, although the risks are still debated.
Goula et al. (2021)	132 health professionals	Radiation safety measures are adequately understood	Ionizing radiation (X-rays and gamma rays)	Many health professionals had poor knowledge of radiation protection measures, leading to improper practices in medical settings.
Guerra-Reyes et al. (2024)	A systematic review of multiple studies on high school students	Misunderstanding of radiation and light, particularly radioactivity	Radiation and light	Traditional didactic models can lead to misconceptions among high school students, including the belief that all radiation is harmful. To reduce these errors, physics education needs inquiry-based methods.
Han and Gogotsi (2023)	Not applicable (review of MXenes studies)	EMI shielding effectiveness is due to the absorption	Microwaves and radio waves	Many materials reflect rather than absorb EM waves. MXenes are promising for shielding via absorption.

Table 1. (continued)

Study	Sample and size	Misconception about radiation	Type of radiation	Main findings
Hull and Hopf (2020)	55 junior high school students in Vienna	Half-life applies to individual atoms; misunderstanding of radioactive decay.	Ionizing radiation (radioactivity)	Students thought individual atoms decayed gradually over time, rather than understanding half-life as a statistical property of many atoms.
Jarrett and Takacs (2020)	229 secondary students in the UK	Students overestimate the contribution of UV radiation to climate change	UV and IR radiation	Students overestimated the proportion of UV radiation in solar energy and misunderstood energy exchanges related to climate change.
Jauchem (1991)	Not applicable (review)	Microwaves, power lines, and video terminals cause cancer	RF and ELF	Misleading scientific reports contribute to the belief that non-ionizing radiation (e.g., microwaves) poses significant health risks.
Kjelsberg (2024)	177 physics students and 869 non-physics students	Physics students are more skeptical about conspiracy theories and supernatural beliefs than other students	General (electromagnetic knowledge used as a basis for skepticism)	Physics students show lower belief in conspiracy theories and supernatural phenomena than non-physics students. These students display stronger scientific skepticism, especially in distinguishing real conspiracies from unfounded ones, suggesting a preselection of students drawn to skepticism rather than the influence of their education.
Kontomaris et al. (2020)	Not applicable (theoretical study)	Non-ionizing radiation, such as from mobile phones, is as dangerous as ionizing radiation.	Non-ionizing (microwaves and RF)	Students often confuse non-ionizing with ionizing radiation. The study provides teaching methods to clarify the difference between the two types.
Kotsis (2024)	Not applicable (review and curriculum recommendations)	Students struggle with differentiating EMR types and interactions	General EMR	Teaching EMR interactions is essential to improve scientific literacy, using real-world applications to boost understanding.
Libarkin et al. (2011)	283 US students (grades 6-12), 33 teachers, 8 scientists	UV and IR are visible forms of light	UV and IR radiation	Many students thought UV and IR were part of the visible light spectrum. Misunderstanding was common among older students and some teachers.
Lin (2014)	104 undergraduate students (52 science, 52 non-science)	Science news reports are complete and scientifically rigorous	General electromagnetic radiation (as covered in various science news)	Science majors demonstrated better critical thinking and use of evidence when critiquing science news reports compared to non-science majors. Non-science students were likelier to accept claims in news reports without questioning the evidence, reflecting a limited understanding of scientific arguments.
Lips et al. (2021)	Not applicable (review)	Low-dose radiation always poses significant health risks	Ionizing radiation	The paper challenges the exaggerated public perception of low-dose radiation risks, advocating for evidence-based communication on minimal risks.
Millar (1994)	144 UK secondary school students	Radiation and radioactive materials are often confused as the same	Ionizing radiation (radioactivity)	Many students believed that objects exposed to radiation could later emit radiation themselves, showing confusion between irradiation and contamination.
Millar and Gill (1996)	144 UK secondary school students (ages 15-16)	Confusion between irradiation and contamination; misunderstanding of radiation spreading	Ionizing radiation	Many students struggled to distinguish between irradiation and contamination, with over 36% providing responses using non-scientific ideas. They also thought radiation effects "spread" similarly to contamination and held misconceptions about radiation absorption and re-emission.
Mishchenko et al. (2011)	Not applicable (theoretical review)	Electromagnetic scattering is a simple process	Light (visible and UV)	Electromagnetic scattering is complex, requiring Maxwell equations for accurate predictions.
Morales López and Tuzón Marco (2022)	191 secondary students, 29 pre-service teachers	Radioactivity is harmful in all forms, and always dangerous	Ionizing radiation	Students and teachers associated radioactivity with danger, showing confusion about contamination and differences between ionizing and non-ionizing radiation.
Neumann (2014)	Not applicable (educational study)	Radiation is artificial, invisible, and always harmful	General electromagnetic radiation	Many students believe that radiation is man-made, invisible, and always dangerous. Therefore, education on natural sources is needed.
Neumann and Hopf (2012)	50 Austrian 9th grade students	Radiation is primarily associated with nuclear energy and is always harmful.	Ionizing and non-ionizing radiation	Most students associated "radiation" with nuclear power and dangers like cancer. Few understood the broader concept of radiation, including non-ionizing types like visible light and IR. Many had emotional and negative responses to the term "radiation."
Plotz (2017)	Literature review of multiple studies on students (age 10-16)	Radiation is only harmful and comes from dangerous sources like nuclear power	General electromagnetic radiation, including UV, IR, and X-rays	Students confused contamination with irradiation and believed all radiation is harmful and did not differentiate between ionizing and non-ionizing radiation. They also did not recognize visible light as radiation. Suggestions were made to address these misconceptions through better educational strategies.

Table 1. (continued)

Study	Sample and size	Misconception about radiation	Type of radiation	Main findings
Plotz and Fitzgerald (2021)	141 students (grades 9-11)	Radiation is harmful and misunderstood	Ionizing radiation	Using superheroes as teaching aids improved students' understanding of radiation types, but some misconceptions about safety persisted.
Plotz and Hollenthoner (2019)	459 students (ages 9-12) from 7 schools in Austria	Radiation is primarily linked to nuclear accidents like Fukushima	General radiation (radioactivity and visible light)	Children's drawings showed radiation was still linked to radioactivity, but there was a significant increase in depictions of cell phones and computer monitors. There was no primary connection to Fukushima, suggesting changing associations over time.
Prather (2005)	180 non-science major physics students	Irradiation and contamination are confused; radiation makes objects radioactive	Ionizing radiation	Many students were unable to differentiate between irradiation and contamination, often believing radiation made objects radioactive.
Qing (2011)	Not applicable (commentary)	Misunderstanding of differential evolution's application to electromagnetics	General electromagnetic problems	Misconceptions about the application of differential evolution in solving electromagnetic problems were clarified.
Shaaban and Shaikh (2018)	506 adolescents and young adults in Saudi Arabia	Mobile base stations and microwaves emit ionizing radiation	RF and microwaves	Most participants believed mobile base stations emit ionizing radiation, highlighting poor EMR knowledge.
Siersma et al. (2021)	12 pre-university Dutch students and 6 teachers	Medical imaging techniques, such as ultrasounds, emit harmful radiation	X-rays and ultrasound (non-ionizing) radiation	Students believed all medical imaging techniques used harmful radiation, misunderstanding the difference between ionizing and non-ionizing radiation.
Suzuki (2012)	Not applicable (observational commentary)	Confusion between radiation and radioactivity	Radiation in general	The public was confused about radiation and radioactivity, especially following the Fukushima disaster. Media exacerbated these misunderstandings.
Taylor et al. (2022)	Not applicable (review article)	UV radiation is the only concern for sun protection in skin of color	Visible light and UV light	Visible light and UV light contribute to skin color photodamaging, including conditions like hyperpigmentation and melasma. Broad-spectrum sunscreens often do not protect against visible light, requiring tinted sunscreens with iron oxides.
Ürek (2021)	138 pre-service teachers in Turkey (science, classroom, and English language teaching)	Misunderstanding of electromagnetic radiation from X-rays and cell phones as universally dangerous	Ionizing (X-rays) and non-ionizing RF radiation	Many participants misunderstood the risks of electromagnetic radiation, confusing different types of EMR (e.g., X-rays, ultrasound, and bluetooth). Awareness levels varied significantly by educational background.
Welbourne et al. (2016)	Not applicable (technical clarification)	Passive infrared (PIR) camera traps only detect heat-in-motion or animals warmer than the ambient environment.	IR radiation	PIR sensors detect changes in IR radiation, not just heat-in-motion. They can trigger with animals that are cooler than the background. Misleading descriptions of PIR function have led to misinterpretations of wildlife data.
Wilson (2019)	Not applicable (review and commentary)	The public believes that all radiation, regardless of type or dose, is harmful.	Ionizing radiation (X-rays and gamma rays)	Public misconceptions about radiation, driven by media and pop culture, lead to overly conservative policies that are not based on current scientific evidence.
Wojcik et al. (2019)	High school students in Sweden	Low-dose ionizing radiation is always harmful	Ionizing radiation (X-rays and gamma rays)	Students misunderstood low-dose radiation risks. Socio-scientific education is necessary for informed decision-making.
Wong et al. (2023)	267 students (95 secondary schools, 172 junior colleges)	Radiation is only emitted by living things; mobile phones cause cancer	Ionizing and non-ionizing radiation (mobile phones and microwaves)	Students believed regular mobile phone use causes cancer and confused natural vs. man-made radiation, viewing the latter as more dangerous.
Wood and Roy (2017)	Not applicable (review and policy recommendations)	Non-ionizing radiation is as harmful as ionizing radiation	RF, ELF, and UV radiation	The study clarifies that non-ionizing radiation poses minimal risks compared to ionizing radiation, with UV radiation being an exception requiring protection.
Zloklikovits and Hopf (2021)	6 middle school students in Vienna	Electromagnetic radiation is tangible and always produces heat	General electromagnetic radiation (IR, visible light, and radio waves)	Students misunderstood the behavior of electromagnetic radiation, believing it is always tangible or produces heat.

Millar (1994) reported that secondary school students in the UK often confuse radiation with radioactivity, believing that any object exposed to radiation becomes radioactive and thus dangerous.

Another widespread misunderstanding pertains to the differences between ionizing and non-ionizing radiation. Ionizing radiation, like X-rays and gamma rays, has enough energy to remove tightly bound electrons from atoms, potentially causing cellular damage. Non-ionizing radiation, such as microwaves and radio waves, lacks this energy and is generally considered safe at typical exposure levels. Gavrilas et al. (2022a) showed that a significant number of university students in Greece incorrectly thought that cell phones and Wi-Fi networks emit harmful radioactivity.

Misunderstandings about blackbody radiation are also prevalent, even among educators. Blackbody radiation refers to the EMR emitted by a body in thermal equilibrium. Some educators believe it only occurs at high temperatures or emits only visible light, neglecting its broader spectrum. Balta (2018) and Bezen et al. (2021) reported that physics teachers and pre-service teachers in Turkey had incomplete knowledge of blackbody radiation, misunderstanding its definition and believing it emits solely at certain wavelengths or temperatures.

Confusion between irradiation and contamination is another common issue. Many individuals mistake irradiation (exposure to radiation) for contamination (having radioactive material on or inside the body). This leads to the false belief that irradiated objects become radioactive themselves. Prather (2005) observed that undergraduate physics students struggled to differentiate between the two concepts, often believing that exposure to radiation makes objects inherently radioactive. Millar and Gill (1996) found that over 36% of secondary students provided non-scientific explanations, thinking radiation effects spread like contamination.

There is also a prevalent belief that exposure to non-ionizing radiation from devices like mobile phones and Wi-Fi networks leads to immediate health issues such as headaches or cancer. Gavrilas and Kotsis (2023b) discovered that 87.6% of university students reported symptoms like headaches after excessive phone use, attributing these symptoms directly to radiation exposure without conclusive scientific evidence.

Some believe radiation is primarily a man-made phenomenon and is always invisible, ignoring natural sources and visible forms of EMR. Neumann and Hopf (2012) noted that Austrian secondary students associated radiation with nuclear power and dangers like cancer, with few understanding that radiation also includes natural and visible forms like sunlight. This limited perception can hinder a comprehensive understanding of the electromagnetic spectrum, and the various types of radiation encountered in everyday life.

Another misconception is that all medical imaging techniques involve harmful radiation, leading to undue fear of medical procedures. Siersma et al. (2021) found that students believed techniques like ultrasounds emit harmful radiation, not realizing that ultrasounds use sound waves, which are non-ionizing and generally safe. This misunderstanding can affect patients' willingness to undergo necessary medical imaging procedures and highlights the need for better public education.

People often think regular sunscreens, including visible light, protect against harmful solar radiation. Geisler et al. (2021) and Taylor et al. (2022) highlighted that traditional sunscreens protect against UV radiation but not visible light, which can also contribute to skin damage. This misconception can lead to inadequate protection against the full spectrum of harmful solar radiation.

There is a belief that electromagnetic field (EMF) exposure primarily comes from public sources like base stations rather than personal devices. Claassen et al. (2017) showed that people often underestimate their exposure from mobile phones and overestimate exposure from sources like base stations, leading to skewed perceptions of risk. This misunderstanding can influence public opinion and policy regarding EMF exposure and safety regulations.

Some think radiation can spread like a contaminant through objects and environments, leading to exaggerated fears of exposure. Plotz (2017) noted that students believed radiation behaves like a substance that can be passed on, not understanding that radiation is energy that does not make objects radioactive. This confusion between radiation and radioactive contamination can cause unnecessary alarm and stigmatization of individuals or objects associated with radiation.

There is a tendency to overestimate the dangers of low-dose ionizing radiation, leading to unnecessary fear and avoidance of beneficial medical procedures. Lips et al. (2021) argued that public perception often exaggerates the risks associated with low-dose radiation, calling for evidence-based communication to correct this misunderstanding. Misconceptions about the risks of low-dose radiation can negatively impact healthcare decisions and policies.

Misconceptions also arise due to the misinterpretation of scientific information in media reports. Students often accept scientific claims in media without critical evaluation, leading to the spread of misconceptions. Lin (2014) found that non-science majors were more likely to accept claims in science news reports without questioning the evidence, indicating a need for improved scientific literacy education. This lack of critical thinking skills can perpetuate misunderstandings and hinder informed decision-making.

Addressing these misconceptions requires targeted educational efforts and clear communication. Educational strategies should incorporate inquiry-based learning and real-world applications to help students understand EMR concepts more deeply (Kotsis, 2024). Improving educators' understanding of EMR is crucial to conveying accurate information (Balta, 2018; Bezen et al., 2021). Public communication should use evidence-based approaches to inform the public about EMR, addressing fears without causing undue alarm (Lips et al., 2021). Encouraging critical thinking when interpreting scientific information from media sources can also help combat misconceptions (Lin, 2014). Misconceptions about EMR are widespread and can significantly affect public health, education, and technology adoption. By identifying and addressing these misunderstandings through targeted educational efforts and clear communication, we can foster a more informed public capable of making better decisions related to EMR.

IMPACT ON SCIENTIFIC LITERACY

Misconceptions about EMR profoundly impact students' scientific literacy, influencing their ability to understand and apply scientific principles effectively. These misunderstandings can deter students from pursuing careers in STEM and contribute to a broader societal issue of scientific illiteracy. When students hold incorrect beliefs about fundamental concepts like EMR, they are less likely to engage meaningfully with science and technology, which can limit their participation in informed decision-making about scientific and technological issues (An & Thomas, 2021; Billingsley & Heyes, 2023; Lei et al., 2019; Phil Canlas, 2024; Sheldrake et al., 2017; Soltani & Askarizadeh, 2021).

Addressing these misconceptions is essential for fostering a scientifically literate population capable of critically evaluating information and making informed choices (Cavagnetto, 2010; Jin et al., 2023; Vieira & Tenreiro-Vieira, 2016). This requires a concerted effort to improve science education by developing comprehensive curricula, employing effective teaching strategies, and providing robust teacher training (Dias Da Silva & Heaton, 2017; Kelp et al., 2023; Turiman et al., 2012). By building a solid foundation of knowledge and critical thinking skills, educators can help students navigate the complex landscape of scientific information and reduce the impact of misinformation on public understanding (Altun & Yildirim, 2023; Gavrilas et al., 2024a; Shamboul, 2022). In conclusion, misconceptions about EMR are pervasive and can significantly hinder scientific literacy. Addressing these issues through improved curricula, innovative teaching methods, and comprehensive teacher training is crucial for fostering a more scientifically literate society.

HEALTH CONCERNS RELATED TO ELECTROMAGNETIC RADIATION EXPOSURE

Public concern about the health effects of EMR has grown considerably in recent years, driven by the widespread use of mobile phones, wireless networks, and other EMR-emitting devices (Jagetia, 2022; Jayaraju et al., 2023; Thill et al., 2023; ZafarAhmed & ZafarAhmed, 2014). Media coverage and online discussions often highlight potential health risks, leading to anxiety and confusion among the general public. While scientific evidence on the health risks of EMR remains inconclusive, the perception of danger persists, influencing public behavior and attitudes (Institute of Electrical and Electronics Engineers [IEEE], 2005; International Commission on Non-Ionizing Radiation Protection [ICNIRP], 2009).

The Role of Misconceptions

Misconceptions about EMR play a significant role in shaping public perception and health anxieties. Many people believe that EMR from devices like mobile phones and Wi-Fi routers poses significant health risks, including cancer and neurological disorders (Gavrilas et al., 2022b). These beliefs can exacerbate health anxieties and contribute to what is known as the nocebo effect (Amanzio et al., 2016; Grosso et al., 2024). The nocebo effect occurs when negative expectations about a harmless substance or phenomenon cause an individual to experience real symptoms (Colloca, 2024; Faasse, 2019; Saunders et al., 2024). In the context of EMR, people who believe that they are being harmed by EMR may experience symptoms such as headaches and dizziness, even when their actual exposure is within safe limits or nonexistent (Aringer et al., 1997; Gavrilas & Kotsis, 2023b; Rubin et al., 2005; Seitz et al., 2005).

Addressing these misconceptions is crucial for reducing unnecessary health fears (Stevens et al., 2023; Williams, 1988). Public education campaigns that provide clear and accurate information about EMR and its effects can help dispel myths and alleviate anxiety. Explaining the difference between ionizing and non-ionizing radiation and their respective health impacts can clarify why typical EMR exposure from mobile phones and Wi-Fi is not harmful (Prlić et al., 2022; Rabiei et al., 2023). Additionally, promoting media literacy and critical thinking skills can empower individuals to assess the credibility of the information they encounter regarding EMR and health.

Scientific Evidence on Health Risks

The scientific community has extensively studied the potential health risks associated with EMR exposure, particularly in relation to mobile phones. IARC (2011) classified radiofrequency (RF) EMFs as “possibly carcinogenic to humans” (group 2B). This classification indicates that there is some evidence suggesting a potential link between EMR and cancer, but it is not conclusive. It is important to note that the IARC classification is based on limited evidence and does not imply that EMR exposure is definitively harmful. Further reviews by organizations such as the ICNIRP (2009) and WHO (2023) have found no conclusive evidence linking typical EMR exposure from mobile phones to adverse health effects. WHO (2014) concluded that there is no established risk of cancer from mobile phone use, while the ICNIRP (2009) reported that exposure to RF fields from mobile phones and wireless networks is within safe limits according to current guidelines.

THE IMPORTANCE OF TEACHING ELECTROMAGNETIC RADIATION

Educating students about EMR is crucial for correcting widespread misconceptions and fostering scientific literacy. A well-rounded understanding of EMR not only prepares students for advanced studies in science but also equips them to make informed decisions in a technology-driven society where EMR plays a significant role (Ambarwati & Suyatna, 2018; Kotsis, 2024).

Curriculum Integration

Incorporating EMR concepts into school curricula is essential for providing students with a coherent and comprehensive understanding of both the physical principles and societal implications of EMR. Kotsis (2024) emphasizes the need for a curriculum that covers the fundamental concepts of EMR, such as the nature of electromagnetic waves, the electromagnetic spectrum, and the distinction between ionizing and non-ionizing radiation. This foundational knowledge is critical not only for grasping the scientific principles but also for understanding the implications of EMR in everyday life, including its applications in communication technologies, medical imaging, and even its role in debates about health and safety (Ambarwati & Suyatna, 2018; Amineh, 2020; Jin, 2023). Despite EMR’s critical role in modern science, many high school curricula still lack comprehensive coverage of its concepts. Educators have proposed an integrated curriculum that connects EMR concepts across various physics topics such as optics, atomic structure, and nuclear physics to address this issue (Kotsis, 2024). This approach fosters a deeper understanding of EMR and highlights its relevance across multiple scientific domains.

Innovative Teaching Methods

Innovative pedagogical approaches are necessary to effectively teach EMR and address common misconceptions. Traditional lecture-based methods may not be sufficient to overcome deeply ingrained misunderstandings (Klein et al., 2023; Opdecam & Everaert, 2019; Saville et al., 2006), as students often hold preconceived notions about EMR that can be resistant to change (Gavrilas & Kotsis, 2023a). Innovative teaching methods such as conceptual change texts, case-based instruction, and interactive activities have proven effective in enhancing student comprehension and correcting misconceptions (Alparslan et al., 2003; Gavrilas et al., 2024b; Özmen et al., 2009; Pacaci et al., 2024; Raza et al., 2019; Taşlidere, 2021; Zafar et al., 2022).

Teacher Training

Teachers are instrumental in shaping students’ understanding of EMR, and their own knowledge and attitudes toward the subject significantly impact their teaching effectiveness (Granziera et al., 2022; OECD, 2013). Unfortunately, research has shown that many teachers themselves hold misconceptions about EMR, particularly regarding its health effects and safety (Gavrilas et al., 2022a). These misunderstandings can lead to the transmission of incorrect information to students, perpetuating myths and misunderstandings (McAfee & Hoffman, 2021; Paull et al., 2022).

To address this issue, targeted teacher training and development are crucial for enhancing educational quality and student outcomes (Dange & Siddaraju 2020; Gavrilas et al., 2024a; Ventista & Brown, 2023) in the context of EMR education. Effective training programs equip teachers with knowledge, modern pedagogical skills, and effective classroom management techniques (Ahmed et al., 2021; Ciraso, 2012; Hyseni Duraku et al., 2022). Ongoing professional development helps educators stay updated on new teaching strategies, technological advancements, and curriculum changes, promoting innovation in the classroom (Germuth, 2018; Hennessy et al., 2022; Lindberg & Olofsson, 2010; Montero-Mesa et al., 2023; Uzorka et al., 2023). Such training can include specialized workshops, seminars, peer collaboration, and mentoring programs focused on EMR education, fostering a growth mindset and reflective practice. Continuous development enables teachers to address diverse learning needs and correct misconceptions, fostering inclusivity and scientific literacy (Darling-Hammond et al., 2020; Ozel et al., 2018). Investing in teacher training and development strengthens the education system by empowering teachers to create dynamic, engaging, and informative learning environments that accurately convey the complexities of EMR.

CONCLUSIONS

EMR is fundamental to both the natural world and technological innovation, yet widespread misconceptions about its nature and effects persist. These misunderstandings–stemming from inadequate education, the complexity of EMR concepts, media misrepresentation, and educators' own misconceptions–have significant implications for public health, science education, technology adoption, and policy-making. They lead to unwarranted health anxieties, resistance to beneficial technologies, and challenges in effectively teaching science.

This comprehensive review highlights the critical need to address these misconceptions through strategic educational reforms. Integrating thorough EMR education into school curricula, employing innovative teaching methods that promote conceptual understanding, and enhancing teacher training programs are essential steps. By equipping students with accurate knowledge and critical thinking skills, we can foster scientific literacy that enables individuals to make informed decisions and engage thoughtfully with technological advancements.

Effective communication among scientists, educators, policymakers, and the public is also paramount. Evidence-based dialogues can bridge the gap between scientific evidence and public perception, dispel unfounded fears, and support informed policy decisions. By promoting a discourse grounded in scientific understanding, we can facilitate the responsible advancement of EMR technologies.

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REFERENCES

Abdo, A. A., Allen, B., Berley, D., Blaufuss, E., Casanova, S., Chen, C., Coyne, D. G., Delay, R. S., Dingus, B. L., Ellsworth, R. W., Fleysher, L., Fleysher, R., Gebauer, I., Gonzalez, M. M., Goodman, J. A., Hays, E., Hoffman, C. M., Kolterman, B. E., Kelley, L. A., …, & Yodh, G. B. (2007). Discovery of TeV gamma-ray emission from the Cygnus region of the Galaxy. *The Astrophysical Journal, 658*(1), L33–L36. https://doi.org/10.1086/513696

Acar Sesen, B., & Ince, E. (2010). The Internet as a source of misconception. *Turkish Online Journal of Educational Technology, 9*(4), 94–100.

Ahmed, H. N., Pasha, A. R., & Malik, M. (2021). The role of teacher training programs in optimizing teacher motivation and professional development skills. *Bulletin of Education and Research, 43*(2), 17–37.

Aiello, G., Lombardo, M., & Baldelli, S. (2024). Exploring vitamin D synthesis and function in cardiovascular health: A narrative review. *Applied Sciences, 14*(11), Article 4339. https://doi.org/10.3390/app14114339

Aïmeur, E., Amri, S., & Brassard, G. (2023). Fake news, disinformation and misinformation in social media: A review. *Social Network Analysis and Mining, 13*(1), Article 30. https://doi.org/10.1007/s13278-023-01028-5

Alparslan, C., Tekkaya, C., & Geban, Ö. (2003). Using the conceptual change instruction to improve learning. *Journal of Biological Education, 37*(3), 133–137. https://doi.org/10.1080/00219266.2003.9655868

Altun, E., & Yildirim, N. (2023). What does critical thinking mean? Examination of pre-service teachers' cognitive structures and definitions for critical thinking. *Thinking Skills and Creativity, 49*, Article 101367. https://doi.org/10.1016/j.tsc.2023.101367

Amanzio, M., Palermo, S., & Benedetti, F. (2016). Nocebo and pain. In M. al'Absi, & M. A. Flaten (Eds.), *Neuroscience of pain, stress, and emotion* (pp. 117–131). Elsevier. https://doi.org/10.1016/B978-0-12-800538-5.00006-6

Ambarwati, D., & Suyatna, A. (2018). Interactive design for self-study and developing students' critical thinking skills in electromagnetic radiation topic. *Journal of Physics: Conference Series, 948*, Article 012039. https://doi.org/10.1088/1742-6596/948/1/012039

Amineh, R. K. (2020). Applications of electromagnetic waves: Present and future. *Electronics, 9*(5), Article 808. https://doi.org/10.3390/electronics9050808

Amoah, A., Jingfu, B., Kwaku, A., & Mawuli, E. S. (2018). Microwave super high frequency (SHF) antenna for (satellite communication systems, radar, aircraft navigation, radio astronomy, remote sensing and communications). In *Proceedings of the IEEE Symposium on Product Compliance Engineering* (pp. 1–8). IEEE. https://doi.org/10.1109/SPCEB.2018.8604474

An, J., & Thomas, N. (2021). Students' beliefs about the role of interaction for science learning and language learning in EMI science classes: Evidence from high schools in China. *Linguistics and Education, 65*, Article 100972. https://doi.org/10.1016/j.linged.2021.100972

Ardito, L., Natalicchio, A., Appio, F. P., & Messeni Petruzzelli, A. (2021). The role of scientific knowledge within inventing teams and the moderating effects of team internationalization and team experience: Empirical tests into the aerospace sector. *Journal of Business Research, 128*, 701–710. https://doi.org/10.1016/j.jbusres.2019.11.022

Aringer, L., Cunningham, J., Gobba, F., Leitgeb, N., Miro, L., Neubauer, G., Ruppe, I., Vecchia, P., & Wadman, C. (1997). Possible health implications of subjective symptoms and electromagnetic fields. *Arbetslivsinstitutet*. https://gupea.ub.gu.se/handle/2077/4156

Azzam, E. I., Jay-Gerin, J.-P., & Pain, D. (2012). Ionizing radiation-induced metabolic oxidative stress and prolonged cell injury. *Cancer Letters, 327*(1–2), 48–60. https://doi.org/10.1016/j.canlet.2011.12.012

Bagatin, M., & Gerardin, S. (Eds). (2020). *Ionizing radiation effects in electronics: From memories to imagers*. CRC Press.

Balta, N. (2018). High school teachers' understanding of blackbody radiation. *International Journal of Science and Mathematics Education, 16*(1), 23–43. https://doi.org/10.1007/s10763-016-9769-z

Bartz, R. J. (2017). *CWTS®, CWS, and CWT complete study guide: Exams PW0-071, CWS-100, CWT-100* (1st ed.). Wiley. https://doi.org/10.1002/9781119419426

Baskar, R., Lee, K. A., Yeo, R., & Yeoh, K.-W. (2012). Cancer and radiation therapy: Current advances and future directions. *International Journal of Medical Sciences, 9*(3), 193–199. https://doi.org/10.7150/ijms.3635

Batool, S., Bibi, A., Frezza, F., & Mangini, F. (2019). Benefits and hazards of electromagnetic waves, telecommunication, physical and biomedical: A review. *European Review for Medical and Pharmacological Sciences, 23*(7), 3121–3128. https://doi.org/10.26355/eurrev_201904_17596

Beauvais, C. (2022). Fake news: Why do we believe it? *Joint Bone Spine, 89*(4), Article 105371. https://doi.org/10.1016/j.jbspin.2022.105371

Bell, B. I., Vercellino, J., Brodin, N. P., Velten, C., Nanduri, L. S. Y., Nagesh, P. K. B., Tanaka, K. E., Fang, Y., Wang, Y., Macedo, R., English, J., Schumacher, M. M., Duddempudi, P. K., Asp, P., Koba, W., Shajahan, S., Liu, L., Tomé, W. A., Yang, W.-L., …, & Guha, C. (2022). Orthovoltage X-rays exhibit increased efficacy compared with γ-rays in preclinical irradiation. *Cancer Research, 82*(15), 2678–2691. https://doi.org/10.1158/0008-5472.CAN-22-0656

Belpomme, D., Hardell, L., Belyaev, I., Burgio, E., & Carpenter, D. O. (2018). Thermal and non-thermal health effects of low intensity non-ionizing radiation: An international perspective. *Environmental Pollution, 242*, 643–658. https://doi.org/10.1016/j.envpol.2018.07.019

Bezen, S., Aykutlu, I., & Bayrak, C. (2021). What does black-body radiation mean for pre-service physics teachers. *Turkish Journal of Science Education, 4*. https://doi.org/10.36681/tused.2021.98

Billingsley, B., & Heyes, J. M. (2023). Preparing students to engage with science- and technology-related misinformation: The role of epistemic insight. *The Curriculum Journal, 34*(2), 335–351. https://doi.org/10.1002/curj.190

Bochner, B. (2021). Electromagnetic wave propagation in general Kasner-like metrics. *arXiv*. https://doi.org/10.1142/S0218271822300166

Bórquez-Sánchez, E. (2024). Scientific literacy in biology and attitudes towards science in the Chilean education system. *Research in Science & Technological Education*. https://doi.org/10.1080/02635143.2024.2320104

Borrego-Soto, G., Ortiz-López, R., & Rojas-Martínez, A. (2015). Ionizing radiation-induced DNA injury and damage detection in patients with breast cancer. *Genetics and Molecular Biology, 38*(4), 420–432. https://doi.org/10.1590/S1415-475738420150019

Boyes, E., & Stanisstreet, M. (1994). Children's ideas about radioactivity and radiation: Sources, mode of travel, uses and dangers. *Research in Science & Technological Education, 12*(2), 145–160. https://doi.org/10.1080/0263514940120204

Bramson, M. A. (1968). *Infrared radiation*. Springer. https://doi.org/10.1007/978-1-4757-0911-7

Bryan, R. N. (Eds). (2001). *Introduction to the science of medical imaging* (1st ed.). Cambridge University Press. https://doi.org/10.1017/CBO9780511994685

Buschke, F. (1961). Common misconceptions in radiation therapy. *The American Journal of Surgery, 101*(2), 164–171. https://doi.org/10.1016/0002-9610(61)90748-6

Carassa, F. (1973). Aspects in using frequencies bands above 10 GHz for satellite communication systems. In A. Zancla (Ed.), *Modern topics in microwave propagation and air-sea interaction* (pp. 258–281). Springer. https://doi.org/10.1007/978-94-010-2681-9_22

Carr, M. W., & Grey, M. L. (2002). Magnetic Resonance Imaging: Overview, risks, and safety measures. *American Journal of Nursing, 102*(12), 26–33. https://doi.org/10.1097/00000446-200212000-00012

Cavagnetto, A. R. (2010). Argument to foster scientific literacy: A review of argument interventions in K-12 science contexts. *Review of Educational Research, 80*(3), 336–371. https://doi.org/10.3102/0034654310376953

Choppin, G., Liljenzin, J.-O., Rydberg, J., & Ekberg, C. (2013). Radiation effects on matter. In G. Choppin, J.-O. Liljenzin, J. Rydberg, & C. Ekberg (Eds.), *Radiochemistry and nuclear chemistry* (4th ed.) (pp. 209–237). Academic Press. https://doi.org/10.1016/B978-0-12-405897-2.00008-2

Ciraso, A. (2012). An evaluation of the effectiveness of teacher training: Some results from a study on the transfer factors of teacher training in Barcelona area. *Procedia-Social and Behavioral Sciences, 46*, 1776–1780. https://doi.org/10.1016/j.sbspro.2012.05.377

Claassen, L., Van Dongen, D., & Timmermans, D. R. M. (2017). Improving lay understanding of exposure to electromagnetic fields; the effect of information on perception of and responses to risk. *Journal of Risk Research, 20*(9), 1115–1131. https://doi.org/10.1080/13669877.2015.1031268

Colloca, L. (2024). The nocebo effect. *Annual Review of Pharmacology and Toxicology, 64*(1), 171–190. https://doi.org/10.1146/annurev-pharmtox-022723-112425

D'Orazio, J., Jarrett, S., Amaro-Ortiz, A., & Scott, T. (2013). UV radiation and the skin. *International Journal of Molecular Sciences, 14*(6), 12222–12248. https://doi.org/10.3390/ijms140612222

Daher, J. K., Harris, J. M., & Wheeler, M. L. (1994). A look at the radio frequency susceptibility of commercial GPS receivers. In *Proceedings of National Aerospace and Electronics Conference* (pp. 164–170). https://doi.org/10.1109/NAECON.1994.332883

Dan, S. S., & Mahapatra, S. (2009). Modeling and analysis of energy quantization effects on single electron inverter performance. *Physica E: Low-Dimensional Systems and Nanostructures, 41*(8), 1410–1416. https://doi.org/10.1016/j.physe.2009.04.004

Dange, J. K. & Siddaraju. (2020). Role of teacher training program in enhancing quality education. *International Journal of Education, Culture and Society, 5*(6), 137–140. https://doi.org/10.11648/j.ijecs.20200506.14

Darling-Hammond, L., Flook, L., Cook-Harvey, C., Barron, B., & Osher, D. (2020). Implications for educational practice of the science of learning and development. *Applied Developmental Science, 24*(2), 97–140. https://doi.org/10.1080/10888691.2018.1537791

Darling-Hammond, L., Schachner, A. C. W., Wojcikiewicz, S. K., & Flook, L. (2024). Educating teachers to enact the science of learning and development. *Applied Developmental Science, 28*(1), 1–21. https://doi.org/10.1080/10888691.2022.2130506

Davydov, A. Y. (2012). Wave-particle duality in classical mechanics. *Journal of Physics: Conference Series, 361*, Article 012029. https://doi.org/10.1088/1742-6596/361/1/012029

Del Vicario, M., Bessi, A., Zollo, F., Petroni, F., Scala, A., Caldarelli, G., Stanley, H. E., & Quattrociocchi, W. (2016). The spreading of misinformation online. *Proceedings of the National Academy of Sciences, 113*(3), 554–559. https://doi.org/10.1073/pnas.1517441113

Deng, X., Huang, H., Huang, S., Yang, M., Wu, J., Ci, Z., He, Y., Wu, Z., Han, L., & Zhang, D. (2022). Insight into the incredible effects of microwave heating: Driving changes in the structure, properties and functions of macromolecular nutrients in novel food. *Frontiers in Nutrition, 9*. https://doi.org/10.3389/fnut.2022.941527

Dias Da Silva, P., & Heaton, L. (2017). Fostering digital and scientific literacy: Learning through practice. *First Monday, 22*(6). https://doi.org/10.5210/fm.v22i6.7284

Dimitrova, T. L., & Weis, A. (2008). The wave-particle duality of light: A demonstration experiment. *American Journal of Physics, 76*(2), 137–142. https://doi.org/10.1119/1.2815364

Directorate-General for Internal Policies of the Union (European Parliament), Siarova, H., Sternadel, D., & Szőnyi, E. (2019). *Science and scientific literacy as an educational challenge: Research for CULT Committee*. Publications Office of the European Union.

Douglas, C. M. W. (2007). Scientific literacy and public understandings of science. In G. Ritzer (Ed.), *The Blackwell encyclopedia of sociology* (1st ed.). Wiley. https://doi.org/10.1002/9781405165518.wbeoss049

Doviak, R. J., & Zrnić, D. S. (1993). Electromagnetic waves and propagation. In R. J. Doviak, & D. S. Zrnić (Eds.), *Doppler radar and weather observations* (pp. 10–29). Elsevier. https://doi.org/10.1016/B978-0-12-221422-6.50007-3

Edvardsen, T., & Rosen, B. D. (2005). Why do we need magnetic resonance imaging in cardiology? *Scandinavian Cardiovascular Journal, 39*(5), 260–263. https://doi.org/10.1080/14017430500405015

Engelmann, C. A., & Huntoon, J. E. (2011). Improving student learning by addressing misconceptions. *Transactions American Geophysical Union, 92*(50), 465–466. https://doi.org/10.1029/2011EO500001

Englander, M. J., & Ghatan, C. (2021). Radiation and the pregnant IR: Myth versus fact. *CardioVascular and Interventional Radiology, 44*(6), 877–882. https://doi.org/10.1007/s00270-020-02704-1

Ergul, O., Dinc, E., & Akan, O. B. (2015). Communicate to illuminate: State-of-the-art and research challenges for visible light communications. *Physical Communication, 17*, 72–85. https://doi.org/10.1016/j.phycom.2015.08.003

Faasse, K. (2019). Nocebo effects in health psychology. *Australian Psychologist, 54*(6), 453–465. https://doi.org/10.1111/ap.12392

Farashi, S., Bashirian, S., Khazaei, S., Khazaei, M., & Farhadinasab, A. (2022). Mobile phone electromagnetic radiation and the risk of headache: A systematic review and meta-analysis. *International Archives of Occupational and Environmental Health, 95*(7), 1587–1601. https://doi.org/10.1007/s00420-022-01835-x

Felder, G. N., & Felder, K. M. (2022). The electromagnetic spectrum. In G. N. Felder, & K. M. Felder (Eds.), *Modern physics* (pp. 713–714). Cambridge University Press. https://doi.org/10.1017/9781108913270.019

Feynman, R. P., Leighton, R. B., Sands, M. L., & Feynman, R. P. (2007). *Mainly mechanics, radiation, and heat*. Addison-Wesley.

Formenti, S. C., Demaria, S., Barcellos-Hoff, M. H., & McBride, W. H. (2016). Subverting misconceptions about radiation therapy. *Nature Immunology, 17*(4), 345–345. https://doi.org/10.1038/ni.3363

Frenzel Jr, L. E. (2010). Radio/wireless. In L. E. Frenzel Jr (Ed.), *Electronics explained* (pp. 147–182). Elsevier. https://doi.org/10.1016/B978-1-85617-700-9.00007-2

Furuta, E., & Kusama, K. (2014). Teaching materials for radiation training and user guides. *Radiation Safety Management, 13*(1), 1–8. https://doi.org/10.12950/rsm.13.1

Gabovich, A. M., & Gabovich, N. A. (2007). How to explain the non-zero mass of electromagnetic radiation consisting of zero-mass photons. *European Journal of Physics, 28*(4), 649–655. https://doi.org/10.1088/0143-0807/28/4/004

Gavrilas, L., & Kotsis, K. T. (2023a). Assessing elementary understanding of electromagnetic radiation and its implementation in wireless technologies among pre-service teachers. *International Journal of Professional Development, Learners and Learning, 5*(2), Article ep2309. https://doi.org/10.30935/ijpdll/13191

Gavrilas, L., & Kotsis, K. T. (2023b). Research for self-reported health problems after excessive talking time on mobile phones among university students. *Eurasian Journal of Science and Environmental Education, 3*(1), 7–15. https://doi.org/10.30935/ejsee/12958

Gavrilas, L., & Kotsis, K. T. (2024). Development and validation of a survey instrument towards attitude, knowledge, and application of educational robotics (Akaer). *International Journal of Research & Method in Education*, 1–23. https://doi.org/10.1080/1743727X.2024.2358780

Gavrilas, L., Kotsis, K. T., & Papanikolaou, M.-S. (2022a). Attitudes and behaviors of university students towards electromagnetic radiation of cell phones and wireless networks. *Aquademia, 6*(2), Article ep22009. https://doi.org/10.30935/aquademia/12393

Gavrilas, L., Kotsis, K. T., & Papanikolaou, M.-S. (2022b). Gender differences in attitudes and behaviors associated with electromagnetic radiation of mobile phones and wireless networks. *International Journal of Educational Innovation, 4*(5), 25-37. https://journal.eepek.gr/assets/uploads/manuscripts/manuf_672_Ex8aVQhIOe.pdf

Gavrilas, L., Kotsis, K. T., & Papanikolaou, M.-S. (2024a). Assessing teacher readiness for educational robotics integration in primary and preschool education. *Education 3-13*, 1–17. https://doi.org/10.1080/03004279.2023.2300699

Gavrilas, L., Papanikolaou, M. – S., & Kotsis, K. T. (2024b). Exploring electricity in early childhood education: A 5E-based learning approach. *Science Activities*, 1–42. https://doi.org/10.1080/00368121.2024.2406208

Gavrilas, L., Papanikolaou, M.-S., & Kotsis, K. T. (2024c). The views of preschool educators on the development of environmental awareness through distance education. *Interdisciplinary Journal of Environmental and Science Education, 20*(3), Article e2411. https://doi.org/10.29333/ijese/14656

Geisler, A. N., Austin, E., Nguyen, J., Hamzavi, I., Jagdeo, J., & Lim, H. W. (2021). Visible light. Part II: Photoprotection against visible and ultraviolet light. *Journal of the American Academy of Dermatology, 84*(5), 1233–1244. https://doi.org/10.1016/j.jaad.2020.11.074

Germuth, A. A. (2018). Professional development that changes teaching and improves learning. *Journal of Interdisciplinary Teacher Leadership, 1*(3), 77–90. https://doi.org/10.46767/kfp.2016-0025

Goiceanu, C., Danulescu, R., Danulescu, E., Tufescu, F. M., & Creanga, D. E. (2011). Exposure to microwaves generated by radar equipment: Case-study and protection issues. *Environmental Engineering and Management Journal, 10*(4), 491–498. https://doi.org/10.30638/eemj.2011.069

Gordon, M. (1994). An outline on electromagnetic radiation and public health. *Reviews on Environmental Health, 10*(3–4). https://doi.org/10.1515/REVEH.1994.10.3-4.149

Goula, A., Chatzis, A., Stamouli, M.-A., Kelesi, M., Kaba, E., & Brilakis, E. (2021). Assessment of health professionals' attitudes on radiation protection measures. *International Journal of Environmental Research and Public Health, 18*(24), Article 13380. https://doi.org/10.3390/ijerph182413380

Granziera, H., Liem, G. A. D., Chong, W. H., Martin, A. J., Collie, R. J., Bishop, M., & Tynan, L. (2022). The role of teachers' instrumental and emotional support in students' academic buoyancy, engagement, and academic skills: A study of high school and elementary school students in different national contexts. *Learning and Instruction, 80*, Article 101619. https://doi.org/10.1016/j.learninstruc.2022.101619

Grimes, D. R. (2022). Radiofrequency radiation and cancer: A review. *JAMA Oncology, 8*(3), Article 456. https://doi.org/10.1001/jamaoncol.2021.5964

Gromkowska-Kępka, K. J., Puścion-Jakubik, A., Markiewicz-Żukowska, R., & Socha, K. (2021). The impact of ultraviolet radiation on skin photoaging–Review of in vitro studies. *Journal of Cosmetic Dermatology, 20*(11), 3427–3431. https://doi.org/10.1111/jocd.14033

Grosso, F., Barbiani, D., Cavalera, C., Volpato, E., & Pagnini, F. (2024). Risk factors associated with nocebo effects: A review of reviews. *Brain, Behavior, & Immunity-Health, 38*, Article 100800. https://doi.org/10.1016/j.bbih.2024.100800

Gudkov, S. V., Andreev, S. N., Barmina, E. V., Bunkin, N. F., Kartabaeva, B. B., Nesvat, A. P., Stepanov, E. V., Taranda, N. I., Khramov, R. N., & Glinushkin, A. P. (2017). Effect of visible light on biological objects: Physiological and pathophysiological aspects. *Physics of Wave Phenomena, 25*(3), 207–213. https://doi.org/10.3103/S1541308X17030074

Guerra-Reyes, F., Guerra-Dávila, E., Naranjo-Toro, M., Basantes-Andrade, A., & Guevara-Betancourt, S. (2024). Misconceptions in the learning of natural sciences: A systematic review. *Education Sciences, 14*(5), Article 497. https://doi.org/10.3390/educsci14050497

Han, B. (2020). Next-generation scientists: Past, present and future. *The Innovation, 1*(2), Article 100037. https://doi.org/10.1016/j.xinn.2020.100037

Han, M., & Gogotsi, Y. (2023). Perspectives for electromagnetic radiation protection with MXenes. *Carbon, 204*, 17–25. https://doi.org/10.1016/j.carbon.2022.12.036

Havránková, R. (2020). Biological effects of ionizing radiation. *Casopis Lekaru Ceskych, 159*(7–8), 258–260.

Heddleson, R. A., & Doores, S. (1994). Factors affecting microwave heating of foods and microwave induced destruction of foodborne pathogens–A review. *Journal of Food Protection, 57*(11), 1025–1037. https://doi.org/10.4315/0362-028X-57.11.1025

Hennessy, S., D'Angelo, S., McIntyre, N., Koomar, S., Kreimeia, A., Cao, L., Brugha, M., & Zubairi, A. (2022). Technology use for teacher professional development in low- and middle-income countries: A systematic review. *Computers and Education Open, 3*, Article 100080. https://doi.org/10.1016/j.caeo.2022.100080

Henriksen, E. K., & Jorde, D. (2001). High school students' understanding of radiation and the environment: Can museums play a role? *Science Education, 85*(2), 189–206. https://doi.org/10.1002/1098-237X(200103)85:2<189::AID-SCE60>3.0.CO;2-S

Heston, T. F., & Tafti, D. (2024). *Nuclear medicine safety*. StatPearls Publishing.

Hewitt, P. G. (2015). *Conceptual physics* (12th ed.). Pearson.

Hill, M. A. (2004). The variation in biological effectiveness of X-rays and gamma rays with energy. *Radiation Protection Dosimetry, 112*(4), 471–481. https://doi.org/10.1093/rpd/nch091

Hoffer, A. J. (2019). Using data and research to address student misconceptions. *International Review of Economics Education, 31*, Article 100156. https://doi.org/10.1016/j.iree.2019.100156

Houston, J. B., Spialek, M. L., & First, J. (2018). Disaster media effects: A systematic review and synthesis based on the differential susceptibility to media effects model. *Journal of Communication, 68*(4), 734–757. https://doi.org/10.1093/joc/jqy023

Hull, M. M., & Hopf, M. (2020). Student understanding of emergent aspects of radioactivity. *International Journal of Physics and Chemistry Education, 12*(2), 19–33.

Hussein, K. I., Alqahtani, M. S., Grelowska, I., Reben, M., Afifi, H., Zahran, H., Yaha, I. S., & Yousef, E. S. (2021). Optically transparent glass modified with metal oxides for X-rays and gamma rays shielding material. *Journal of X-Ray Science and Technology, 29*(2), 331–345. https://doi.org/10.3233/XST-200780

Hyseni Duraku, Z., Blakaj, V., Shllaku Likaj, E., Boci, L., & Shtylla, H. (2022). Professional training improves early education teachers' knowledge, skills, motivation, and self-efficacy. *Frontiers in Education, 7*. https://doi.org/10.3389/feduc.2022.980254

IARC Working Group on the Evaluation of Carcinogenic Risks to Humans. (2012). *Radiation (IARC monographs on the evaluation of carcinogenic risks to humans)*. International Agency for Research on Cancer.

IARC. (2011). *IARC monographs on the evaluation of carcinogenic risks to humans, supplement 7: Overall evaluations of carcinogenicity: An update of IARC monographs volumes 1–42*. International Agency for Research on Cancer.

Ichihashi, M., Ueda, M., Budiyanto, A., Bito, T., Oka, M., Fukunaga, M., Tsuru, K., & Horikawa, T. (2003). UV-induced skin damage. *Toxicology, 189*(1–2), 21–39. https://doi.org/10.1016/S0300-483X(03)00150-1

ICNIRP. (2009). *Statement on the guidelines for limiting exposure to time-varying electric, magnetic and electromagnetic fields (up to 300 GHz)*. International Commission on Non-Ionizing Radiation Protection.

Idris, A. N., Sathyamoorthy, D., Suldi, A. M., & Hamid, J. R. A. (2014). Effect of radio frequency interference (RFI) on the precision of GPS relative positioning. *IOP Conference Series: Earth and Environmental Science, 18*, Article 012035. https://doi.org/10.1088/1755-1315/18/1/012035

IEEE. (2005). *IEEE standard for safety levels with respect to human exposure to radiofrequency electromagnetic fields, 3 kHz to 300 GHz* (IEEE Std C95.1). Institute of Electrical and Electronics Engineers.

Ishimaru, A. (2017). *Electromagnetic wave propagation, radiation, and scattering: From fundamentals to applications* (1st ed.). Wiley. https://doi.org/10.1002/9781119079699

Jagetia, G. C. (2022). Genotoxic effects of electromagnetic field radiations from mobile phones. *Environmental Research, 212*(Pt D), Article 113321. https://doi.org/10.1016/j.envres.2022.113321

Jarrett, L., & Takacs, G. (2020). Secondary students' ideas about scientific concepts underlying climate change. *Environmental Education Research, 26*(3), 400–420. https://doi.org/10.1080/13504622.2019.1679092

Jauchem, J. R. (1995). Alleged health effects of electromagnetic fields: The misconceptions continue. *Journal of Microwave Power and Electromagnetic Energy, 30*(3), 165–177. https://doi.org/10.1080/08327823.1995.11688273

Jauchern, J. (1991). Alleged health effects of electromagnetic fields: Misconceptions in the scientific literature. *Journal of Microwave Power and Electromagnetic Energy, 26*(4), 189–195. https://doi.org/10.1080/08327823.1991.11688156

Jayaraju, N., Pramod Kumar, M., Sreenivasulu, G., Lakshmi Prasad, T., Lakshmanna, B., Nagalaksmi, K., & Madakka, M. (2023). Mobile phone and base stations radiation and its effects on human health and environment: A review. *Sustainable Technology and Entrepreneurship, 2*(2), Article 100031. https://doi.org/10.1016/j.stae.2022.100031

Jia, C., Wang, Q., Yao, X., & Yang, J. (2021). The role of DNA damage induced by low/high dose ionizing radiation in cell carcinogenesis. *Exploratory Research and Hypothesis in Medicine, 6*(4), 177–184. https://doi.org/10.14218/ERHM.2021.00020

Jin, G., Wodika, A., Darner, R., & Lai, J. (2023). Fostering scientific literacy with problem sets that generate cognitive presence and fulfill basic psychological needs. *Journal of College Science Teaching, 52*(7), 85–95. https://doi.org/10.1080/0047231X.2023.12315883

Jin, Z. (2023). Analysis of electromagnetic wave applications and development. *Highlights in Science, Engineering and Technology, 68*, 172–181. https://doi.org/10.54097/hset.v68i.12061

Johnson, L., Roan, C., Costa, M., Aung, H. H., & Marks, D. C. (2022). Gamma and X-ray irradiation do not affect the in vitro quality of refrigerated apheresis platelets in platelet additive solution (PAS-E). *Transfusion, 62*(S1). https://doi.org/10.1111/trf.16983

Joseph, A. M., Fernandez, V., Kritzman, S., Eaddy, I., Cook, O. M., Lambros, S., Jara Silva, C. E., Arguelles, D., Abraham, C., Dorgham, N., Gilbert, Z. A., Chacko, L., Hirpara, R. J., Mayi, B. S., & Jacobs, R. J. (2022). COVID-19 misinformation on social media: A scoping review. *Cureus, 14*(4), Article e24601 https://doi.org/10.7759/cureus.24601

Junying, B., & Yongli, A. (2019). Research and development of millimeter wave technology. *International Journal of Advanced Network, Monitoring and Controls, 4*(3), 73–78. https://doi.org/10.21307/ijanmc-2019-061

Karmakar, A. (2016). SiRF technology for satellite and RADAR use. In *Proceedings of the 2016 International Conference on Microelectronics, Computing and Communications* (pp. 1–6). https://doi.org/10.1109/MicroCom.2016.7522492

Kawase, T., Kamiya, M., Hayama, K., Nagata, M., Okuda, K., Yoshie, H., Burns, D. M., Tsuchimochi, M., & Nakata, K. (2015). X-ray and ultraviolet C irradiation-induced γ-H2AX and p53 formation in normal human periosteal cells *in vitro*: Markers for quality control in cell therapy. *Cytotherapy, 17*(1), 112–123. https://doi.org/10.1016/j.jcyt.2014.08.005

Kelp, N. C., McCartney, M., Sarvary, M. A., Shaffer, J. F., & Wolyniak, M. J. (2023). Developing science literacy in students and society: Theory, research, and practice. *Journal of Microbiology & Biology Education, 24*(2), Article e00058-23. https://doi.org/10.1128/jmbe.00058-23

Kendeou, P., & Johnson, V. (2024). The nature of misinformation in education. *Current Opinion in Psychology, 55*, Article 101734. https://doi.org/10.1016/j.copsyc.2023.101734

Kjelsberg, R. (2024). Skepticism and physics: Epistemic beliefs of Norwegian physics students compared with other student groups. *Discover Education, 3*(1), Article 78. https://doi.org/10.1007/s44217-024-00153-3

Klein, K., Calabrese, J., Aguiar, A., Mathew, S., Ajani, K., Almajid, R., & Aarons, J. (2023). Evaluating active lecture and traditional lecture in higher education. *Journal on Empowering Teaching Excellence, 7*(2), Article 6.

Kochetova, G. V., Avercheva, O. V., Bassarskaya, E. M., & Zhigalova, T. V. (2022). Light quality as a driver of photosynthetic apparatus development. *Biophysical Reviews, 14*(4), 779–803. https://doi.org/10.1007/s12551-022-00985-z

Kontomaris, S. V., Malamou, A., Balogiannis, G., & Antonopoulou, N. (2020). A simplified approach for presenting the differences between ionising and non-ionising electromagnetic radiation. *Physics Education, 55*(2), Article 025007. https://doi.org/10.1088/1361-6552/ab5c00

Kotsis, K. T. (2023). Alternative ideas about concepts of physics, a timelessly valuable tool for physics education. *Eurasian Journal of Science and Environmental Education, 3*(2), 83–97. https://doi.org/10.30935/ejsee/13776

Kotsis, K. T. (2024). The importance of teaching electromagnetic radiation interaction in high schools. *Journal of Science Education Research, 8*(2), 142–151. https://doi.org/10.21831/jser.v8i2.76537

Kotsis, K. T., & Stylos, G. (2023). Relationship of IQ with alternative ideas of primary school students on the concepts of force and weight. *European Journal of Education and Pedagogy, 4*(1), 21–25. https://doi.org/10.24018/ejedu.2023.4.1.544

Krawczyk, A., Korzeniewska, E., & Stando, J. (2020). Electromagnetic field in social perception–Myths and conspiracy theories. In *Proceedings of the IEEE Problems of Automated Electrodrive. Theory and Practice* (pp. 1–4). https://doi.org/10.1109/PAEP49887.2020.9240831

Kuenzer, C., & Dech, S. (Eds). (2013). *Thermal infrared remote sensing: Sensors, methods, applications*. Springer. https://doi.org/10.1007/978-94-007-6639-6

Lacomme, P., Hardange, J.-P., Marchais, J.-C., & Normant, E. (2001). Synthetic aperture radar. In *Air and spaceborne radar systems* (pp. 233–264). Elsevier. https://doi.org/10.1016/B978-189112113-5.50017-6

Lahir, Y. K. (2023). Non-ionizing radiations and their biochemical and biomedical impacts: A review. *Journal of Radiation and Cancer Research, 14*(2), 53–66. https://doi.org/10.4103/jrcr.jrcr_17_22

Laitinen, H., Kaunonen, M., & Åstedt-Kurki, P. (2014). The impact of using electronic patient records on practices of reading and writing. *Health Informatics Journal, 20*(4), 235–249. https://doi.org/10.1177/1460458213492445

Lamb, G. M., & Gedroyc, W. M. W. (1997). Interventional magnetic resonance imaging. *British Journal of Radiology, 70*(Special-Issue-1), S81–S88. https://doi.org/10.1259/bjr.1997.0011

Lei, R. F., Green, E. R., Leslie, S., & Rhodes, M. (2019). Children lose confidence in their potential to "be scientists," but not in their capacity to "do science". *Developmental Science, 22*(6), Article e12837. https://doi.org/10.1111/desc.12837

Li, J.-K., Sun, K., Wang, Y., Hao, Z.-Y., Liu, Z.-H., Zhou, J., Fan, X.-Y., Chen, J.-L., Xu, J.-S., Li, C.-F., & Guo, G.-C. (2023). Experimental demonstration of separating the wave-particle duality of a single photon with the quantum Cheshire cat. *Light: Science & Applications, 12*(1), Article 18. https://doi.org/10.1038/s41377-022-01063-5

Libarkin, J. C., Asghar, A., Crockett, C., & Sadler, P. (2011). Invisible misconceptions: Student understanding of ultraviolet and infrared radiation. *Astronomy Education Review, 10*(1), Article 010112. https://doi.org/10.3847/AER2011022

Lin, S.-S. (2014). Science and non-science undergraduate students' critical thinking and argumentation performance in reading a science news report. *International Journal of Science and Mathematics Education, 12*(5), 1023–1046. https://doi.org/10.1007/s10763-013-9451-7

Lindberg, J. O., & Olofsson, A. D. (Eds). (2010). *Online learning communities and teacher professional development: Methods for improved education delivery*. IGI Global. https://doi.org/10.4018/978-1-60566-780-5

Lips, M., Anderson, E., Nakamura, T., Harris, F., Schneider, G., Zic, J., Sanders, C., Owen, J., Hondros, J., & De Ruvo, A. (2021). Reflections on low-dose radiation, the misconceptions, reality and moving forward. *Journal of Radiological Protection, 41*(4), S306–S316. https://doi.org/10.1088/1361-6498/ac1a5d

Liu, T.-F., Shan, H., Wang, H.-Q., & Luan, F.-J. (2021). Ionizing radiation exposure and cancer risks: Matter or not matter? *Spine, 46*(4), Article E286. https://doi.org/10.1097/BRS.0000000000003848

Lopes, R. M., Comarú, M. W., Pierini, M. F., De Souza, R. A., & Hauser-Davis, R. A. (2024). Scientific communication and scientific literacy for the public perception of the importance of environmental quality for public health. *Frontiers in Communication, 9*. https://doi.org/10.3389/fcomm.2024.1297246

Luo, H., Cai, M., & Cui, Y. (2021). Spread of misinformation in social networks: Analysis based on Weibo tweets. *Security and Communication Networks*. https://doi.org/10.1155/2021/7999760

Maayah, Y., Nusrat, H., Pang, G., & Tambasco, M. (2022). Assessing the DNA damaging effectiveness of ionizing radiation using plasmid DNA. *International Journal of Molecular Sciences, 23*(20), Article 12459. https://doi.org/10.3390/ijms232012459

Mandinach, E. B., & Schildkamp, K. (2021). Misconceptions about data-based decision making in education: An exploration of the literature. *Studies in Educational Evaluation, 69*, Article 100842. https://doi.org/10.1016/j.stueduc.2020.100842

Martino, D. (2023). Energy quantization for Willmore surfaces with bounded index. *arXiv*. https://doi.org/10.48550/ARXIV.2305.08668

Matsumura, Y., & Ananthaswamy, H. N. (2004). Toxic effects of ultraviolet radiation on the skin. *Toxicology and Applied Pharmacology, 195*(3), 298–308. https://doi.org/10.1016/j.taap.2003.08.019

McAfee, M., & Hoffman, B. (2021). The morass of misconceptions: How unjustified beliefs influence pedagogy and learning. *International Journal for the Scholarship of Teaching and Learning, 15*(1). https://doi.org/10.20429/ijsotl.2021.150104

McGowan, A., Dowley, A., & Ryan, M.-L. (2023). An assessment of radiation safety practices for transgender and gender non-binary patients in Irish radiology departments. *Radiography, 29*(6), 1021–1028. https://doi.org/10.1016/j.radi.2023.08.004

Mehdipour, A., Yousefi-Ahmadipour, A., Kennedy, D., & Kazemi Arababadi, M. (2021). Ionizing radiation and toll like receptors: A systematic review article. *Human Immunology, 82*(6), 446–454. https://doi.org/10.1016/j.humimm.2021.03.008

Merckel, C. (1972). Microwave and man–The direct and indirect hazards, and the precautions. *California Medicine, 117*(1), 20–24.

Meyer, T., & Stockfleth, E. (2021). Light and skin. In C. Surber, & U. Osterwalder (Eds.), *Current problems in dermatology* (v. 55, pp. 53–61). S. Karger AG. https://doi.org/10.1159/000517592

Millar, R. (1994). School students' understanding of key ideas about radioactivity and ionizing radiation. *Public Understanding of Science, 3*(1), 53–70. https://doi.org/10.1088/0963-6625/3/1/004

Millar, R., & Gill, J. S. (1996). School students' understanding of processes involving radioactive substances and ionizing radiation. *Physics Education, 31*(1), 27–33. https://doi.org/10.1088/0031-9120/31/1/019

Millar, R., Klaassen, K., & Eijkelhof, H. (1990). Teaching about radioactivity and ionising radiation: An alternative approach. *Physics Education, 25*(6), 338–342. https://doi.org/10.1088/0031-9120/25/6/310

Miousse, I. R., Kutanzi, K. R., & Koturbash, I. (2017). Effects of ionizing radiation on DNA methylation: From experimental biology to clinical applications. *International Journal of Radiation Biology, 93*(5), 457–469. https://doi.org/10.1080/09553002.2017.1287454

Mishchenko, M. I., Tishkovets, V. P., Travis, L. D., Cairns, B., Dlugach, J. M., Liu, L., Rosenbush, V. K., & Kiselev, N. N. (2011). Electromagnetic scattering by a morphologically complex object: Fundamental concepts and common misconceptions. *Journal of Quantitative Spectroscopy and Radiative Transfer, 112*(4), 671–692. https://doi.org/10.1016/j.jqsrt.2010.03.016

Mladenova, V., Mladenov, E., Stuschke, M., & Iliakis, G. (2022). DNA damage clustering after ionizing radiation and consequences in the processing of chromatin breaks. *Molecules, 27*(5), Article 1540. https://doi.org/10.3390/molecules27051540

Montero-Mesa, L., Fraga-Varela, F., Vila-Couñago, E., & Rodríguez-Groba, A. (2023). Digital technology and teacher professional development: Challenges and contradictions in compulsory education. *Education Sciences, 13*(10), Article 1029. https://doi.org/10.3390/educsci13101029

Morales López, A. I., & Tuzón Marco, P. (2022). Misconceptions, knowledge, and attitudes towards the phenomenon of radioactivity. *Science & Education, 31*(2), 405–426. https://doi.org/10.1007/s11191-021-00251-w

Mosayebnia, M., Ahmadi, M., Emzhik, M., & Hajiramezanali, M. (2023). Gamma-ray involved in cancer therapy and imaging. In M. Khafaji, & O. Bavi (Eds.), *Electromagnetic waves-based cancer diagnosis and therapy* (pp. 295–345). Academic Press. https://doi.org/10.1016/B978-0-323-99628-0.00003-4

Mubeen, S. M., Abbas, Q., & Nisar, N. (2008). Knowledge about ionising and non-ionising radiation among medical students. *Journal of Ayub Medical College, 20*(1), 118–121.

Muhammed T, S., & Mathew, S. K. (2022). The disaster of misinformation: A review of research in social media. *International Journal of Data Science and Analytics, 13*(4), 271–285. https://doi.org/10.1007/s41060-022-00311-6

Nallanthighal, S., Shirode, A. B., Judd, J. A., & Reliene, R. (2016). Pomegranate intake protects against genomic instability induced by medical X-rays in vivo in mice. *Nutrition and Cancer, 68*(8), 1349–1356. https://doi.org/10.1080/01635581.2016.1225104

Narla, S., Kohli, I., Hamzavi, I. H., & Lim, H. W. (2020). Visible light in photodermatology. *Photochemical & Photobiological Sciences, 19*(1), 99–104. https://doi.org/10.1039/c9pp00425d

Neinavaz, E., Schlerf, M., Darvishzadeh, R., Gerhards, M., & Skidmore, A. K. (2021). Thermal infrared remote sensing of vegetation: Current status and perspectives. *International Journal of Applied Earth Observation and Geoinformation, 102*, Article 102415. https://doi.org/10.1016/j.jag.2021.102415

Neumann, S. (2014). Three misconceptions about radiation–And what we teachers can do to confront them. *The Physics Teacher, 52*(6), 357–359. https://doi.org/10.1119/1.4893090

Neumann, S., & Hopf, M. (2012). Students' conceptions about 'radiation': Results from an explorative interview study of 9th grade students. *Journal of Science Education and Technology, 21*(6), 826–834. https://doi.org/10.1007/s10956-012-9369-9

Neumann, S., & Hopf, M. (2013). Students' ideas about nuclear radiation–Before and after Fukushima. *Eurasia Journal of Mathematics, Science and Technology Education, 9*(4), 393–404. https://doi.org/10.12973/eurasia.2014.948a

Nygren, T., Frau-Meigs, D., Corbu, N., & Santoveña-Casal, S. (2022). Teachers' views on disinformation and media literacy supported by a tool designed for professional fact-checkers: Perspectives from France, Romania, Spain and Sweden. *SN Social Sciences, 2*(4), Article 40. https://doi.org/10.1007/s43545-022-00340-9

OECD. (2005). *Health technologies and decision making.* OECD Publishing. https://doi.org/10.1787/9789264016224-en

OECD. (2013). *The role of teachers and schools in shaping students' engagement, drive and self-beliefs.* OECD Publishing. https://doi.org/10.1787/9789264201170-9-en

OECD. (2023). Communicating science responsibly. OECD Publishing. https://doi.org/10.1787/5c3be7ce-en

Opdecam, E., & Everaert, P. (2019). Choice-based learning: Lecture-based or team learning? *Accounting Education, 28*(3), 239–273. https://doi.org/10.1080/09639284.2019.1570857

Osepchuk, J. M. (2009). The history of the microwave oven: A critical review. In *Proceedings of the IEEE MTT-S International Microwave Symposium Digest* (pp. 1397–1400). https://doi.org/10.1109/MWSYM.2009.5165967

Østerlind, A. (1993). Cancer and UV-radiation. *Pharmacology & Toxicology, 72*(s1), 67–68. https://doi.org/10.1111/j.1600-0773.1993.tb01672.x

Ozel, E., Ganesan, M. Z., Daud, A. K. M., Darusalam, G. B., & Ali, N. A. B. N. (2018). Critical issue teacher training into inclusive education. *Advanced Science Letters, 24*(7), 5139–5142. https://doi.org/10.1166/asl.2018.11288

Özmen, H., Demircioğlu, H., & Demircioğlu, G. (2009). The effects of conceptual change texts accompanied with animations on overcoming 11th grade students' alternative conceptions of chemical bonding. *Computers & Education, 52*(3), 681–695. https://doi.org/10.1016/j.compedu.2008.11.017

Pacaci, C., Ustun, U., & Ozdemir, O. F. (2024). Effectiveness of conceptual change strategies in science education: A meta-analysis. *Journal of Research in Science Teaching, 61*(6), 1263–1325. https://doi.org/10.1002/tea.21887

Panagou, D., Kostara, C., Dimos, E., Stylos, G., & Kotsis, K. (2024). Honors high school graduates students' misconceptions regarding evolutionary theory of biology. *EIKI Journal of Effective Teaching Methods, 2*(3). https://doi.org/10.59652/jetm.v2i3.188

Paull, M., Holmes, K., Omari, M., Haski-Leventhal, D., MacCallum, J., Young, S., & Scott, R. (2022). Myths and misconceptions about university student volunteering: Development and perpetuation. *International Journal of Voluntary and Nonprofit Organizations, 33*(4), 833–845. https://doi.org/10.1007/s11266-021-00437-4

Pereira, G. C., Traughber, M., & Muzic, R. F. (2014). The role of imaging in radiation therapy planning: Past, present, and future. *BioMed Research International*. https://doi.org/10.1155/2014/231090

Phil Canlas, I. (2024). Attitude matters more: The impact of perceived competence and attitudes toward science on science engagement among university students. *International Journal of Science Education*. https://doi.org/10.1080/09500693.2024.2354943

Plotz, T. (2017). Students' conceptions of radiation and what to do about them. *Physics Education, 52*(1), Article 014004. https://doi.org/10.1088/1361-6552/52/1/014004

Plotz, T., & Fitzgerald, B. W. (2021). Superheroes of the electromagnetic spectrum: A non-traditional way of teaching ionising radiation. *Eurasia Journal of Mathematics, Science and Technology Education, 17*(6), Article em1975. https://doi.org/10.29333/ejmste/10901

Plotz, T., & Hollenthoner, F. (2019). Replicating a study about children's drawings concerning radiation. *Multidisciplinary Journal for Education, Social and Technological Sciences, 6*(1), Article 71. https://doi.org/10.4995/muse.2019.10390

Plotz, T., & Hopf, M. (2016). Two concepts of radiation.: A case study to investigate existing preconceptions. *European Journal of Science and Mathematics Education, 4*(4), 447–459. https://doi.org/10.30935/scimath/9484

Poirier, Y., Belley, M. D., Dewhirst, M. W., Yoshizumic, T. T., & Down, J. D. (2020). Transitioning from gamma rays to X rays for comparable biomedical research irradiations: Energy matters. *Radiation Research, 193*(6), Article 506. https://doi.org/10.1667/RADE-20-00039.1

Pozo-Rico, T., Gilar-Corbí, R., Izquierdo, A., & Castejón, J.-L. (2020). Teacher training can make a difference: Tools to overcome the impact of COVID-19 on primary schools. An experimental study. *International Journal of Environmental Research and Public Health, 17*(22), Article 8633. https://doi.org/10.3390/ijerph17228633

Prangnell, L. (2016). Visible light-based human visual system conceptual model. *arXiv*. https://doi.org/10.48550/ARXIV.1609.04830

Prather, E. (2005). Students' beliefs about the role of atoms in radioactive decay and half-life. *Journal of Geoscience Education, 53*(4), 345–354. https://doi.org/10.5408/1089-9995-53.4.345

Prlić, I., Šiško, J., Varnai, V. M., Pavelić, L., Macan, J., Kobešćak, S., Hajdinjak, M., Jurdana, M., Cerovac, Z., Zauner, B., Mihić, M. S., & Avdagić, S. C. (2022). Wi-Fi technology and human health impact: A brief review of current knowledge. *Archives of Industrial Hygiene and Toxicology, 73*(2), 94–106. https://doi.org/10.2478/aiht-2022-73-3402

Prokop, A.-T., & Nawrodt, R. (2024). Energy as a source of preservice teachers' conceptions about radioactivity. *Physical Review Physics Education Research, 20*(1), Article 010155. https://doi.org/10.1103/PhysRevPhysEducRes.20.010155

Puneet, K., Chakraborty, S. K., & Lalita. (2022). Infrared radiation: Principles and applications in food processing. In N. Kumar, A. Panghal, & M. K. Garg (Eds.), *Thermal food engineering operations* (pp. 349–373). Wiley. https://doi.org/10.1002/9781119776437.ch12

Qing, A. (2011). Comment on "differential evolution as applied to electromagnetics". *IEEE Antennas and Propagation Magazine, 53*(4), 169–171. https://doi.org/10.1109/MAP.2011.6097316

Qu, J.-H., Liu, D., Cheng, J.-H., Sun, D.-W., Ma, J., Pu, H., & Zeng, X.-A. (2015). Applications of near-infrared spectroscopy in food safety evaluation and control: A review of recent research advances. *Critical Reviews in Food Science and Nutrition, 55*(13), 1939–1954. https://doi.org/10.1080/10408398.2013.871693

Rabiei, M., Masoumi, S. J., Mortazavi, S. M. J., Nematolahi, S., & Haghani, M. (2023). Mobile cellular data and Wi-Fi use are not associated with adverse health effects. *Journal of Biomedical Physics & Engineering, 13*(6), 497–502. https://doi.org/10.31661/jbpe.v0i0.2206-1511

Rahman, N., Khan, R., & Badshah, S. (2018). Effect of X-rays and gamma radiations on the bone mechanical properties: Literature review. *Cell and Tissue Banking, 19*(4), 457–472. https://doi.org/10.1007/s10561-018-9736-8

Raza, S. A., Qazi, W., & Umer, B. (2019). Examining the impact of case-based learning on student engagement, learning motivation and learning performance among university students. *Journal of Applied Research in Higher Education, 12*(3), 517–533. https://doi.org/10.1108/JARHE-05-2019-0105

Reeve, T. (Eds). (2018). *Ionizing radiation: Advances in research and applications*. Nova Science Publishers.

Reisz, J. A., Bansal, N., Qian, J., Zhao, W., & Furdui, C. M. (2014). Effects of ionizing radiation on biological molecules–Mechanisms of damage and emerging methods of detection. *Antioxidants & Redox Signaling, 21*(2), 260–292. https://doi.org/10.1089/ars.2013.5489

Rizzi, A., & Bonanomi, C. (2012). Colour illusions and the human visual system. In J. Best (Ed.), *Colour design* (pp. 83–104). Woodhead Publishing. https://doi.org/10.1533/9780857095534.1.83

Rodrigues, C., & Singhal, T. (2024). What is new in the diagnosis of childhood tuberculosis? *Indian Journal of Pediatrics, 91*(7), 717–723. https://doi.org/10.1007/s12098-023-04992-0

Rodrigues, F., Newell, R., Rathnaiah Babu, G., Chatterjee, T., Sandhu, N. K., & Gupta, L. (2024). The social media Infodemic of health-related misinformation and technical solutions. *Health Policy and Technology, 13*(2), Article 100846. https://doi.org/10.1016/j.hlpt.2024.100846

Rowley, J., & Mazar, H. (2021). Misunderstandings about radiofrequency electromagnetic field exposure and 5G misinformation. In *Proceedings of the IEEE International Conference on Microwaves, Antennas, Communications and Electronic Systems* (pp. 219–221). https://doi.org/10.1109/COMCAS52219.2021.9629063

Rubin, G. J., Munshi, J. D., & Wessely, S. (2005). Electromagnetic hypersensitivity: A systematic review of provocation studies. *Psychosomatic Medicine, 67*(2), 224–232. https://doi.org/10.1097/01.psy.0000155664.13300.64

Saric-Bosanac, S. S., Clark, A. K., Nguyen, V., Pan, A., Chang, F.-Y., Li, C.-S., & Sivamani, R. K. (2019). Quantification of ultraviolet (UV) radiation in the shade and in direct sunlight. *Dermatology Online Journal, 25*(7), Article 13030/qt4wc0f6tw. https://doi.org/10.5070/D3257044801

Sasanuma, H., Yamada, S., Tsuda, M., & Takeda, S. (2020). Restoration of ligatable "clean" double-strand break ends is the rate-limiting step in the rejoining of ionizing-radiation-induced DNA breakage. *DNA Repair, 93*, Article 102913. https://doi.org/10.1016/j.dnarep.2020.102913

Sasiela, R. J. (1994). *Electromagnetic wave propagation in turbulence*. Springer. https://doi.org/10.1007/978-3-642-85070-7

Saunders, C., Tan, W., Faasse, K., Colagiuri, B., Sharpe, L., & Barnes, K. (2024). The effect of social learning on the nocebo effect: A systematic review and meta-analysis with recommendations for the future. *Health Psychology Review*. https://doi.org/10.1080/17437199.2024.2394682

Saville, B. K., Zinn, T. E., Neef, N. A., Norman, R. V., & Ferreri, S. J. (2006). A comparison of interteaching and lecture in the college classroom. *Journal of Applied Behavior Analysis, 39*(1), 49–61. https://doi.org/10.1901/jaba.2006.42-05

Schmidt, F. N., Hahn, M., Stockhausen, K. E., Rolvien, T., Schmidt, C., Knopp, T., Schulze, C., Püschel, K., Amling, M., & Busse, B. (2022). Influence of X-rays and gamma-rays on the mechanical performance of human bone factoring out intraindividual bone structure and composition indices. *Materials Today Bio, 13*, Article 100169. https://doi.org/10.1016/j.mtbio.2021.100169

Schuette, C., Streuber, M., Pottgiesser, V., Preim, B., Saalfeld, P., Vahlbruch, J.-W., & Walther, C. (2023). A teaching concept for school experiments on radioactivity using augmented reality methods. *Radiation Protection Dosimetry, 199*(8–9), 716–724. https://doi.org/10.1093/rpd/ncad071

Seitz, H., Stinner, D., Eikmann, Th., Herr, C., & Röösli, M. (2005). Electromagnetic hypersensitivity (EHS) and subjective health complaints associated with electromagnetic fields of mobile phone communication–A literature review published between 2000 and 2004. *Science of The Total Environment, 349*(1–3), 45–55. https://doi.org/10.1016/j.scitotenv.2005.05.009

Shaaban, H., & Shaikh, M. B. (2018). Radiation and its associated health risks: Assessment of knowledge and risk perception among adolescents and young adults in Saudi Arabia. *International Journal of Adolescent Medicine and Health, 33*(1), Article 20180056. https://doi.org/10.1515/ijamh-2018-0056

Shamboul, H. A. E. (2022). The importance of critical thinking on teaching learning process. *Open Journal of Social Sciences, 10*(1), 29–35. https://doi.org/10.4236/jss.2022.101003

Shayanfar, S., & Pillai, S. D. (Eds). (2022). *Ionizing radiation technologies: Managing and extracting value from wastes* (1st ed.). Wiley. https://doi.org/10.1002/9781119488583

Sheldrake, R., Mujtaba, T., & Reiss, M. J. (2017). Science teaching and students' attitudes and aspirations: The importance of conveying the applications and relevance of science. *International Journal of Educational Research, 85*, 167–183. https://doi.org/10.1016/j.ijer.2017.08.002

Shibata, J., Takeuchi, A., Kohno, H., & Tatara, G. (2017). Theory of electromagnetic wave propagation in ferromagnetic Rashba conductor. *arXiv*. https://doi.org/10.1063/1.5011130

Shortland, M. (1988). Advocating science: Literacy and public understanding. *Impact of Science on Society, 38*(4), 305–316.

Siani, A., Joseph, M., & Dacin, C. (2024). Susceptibility to scientific misinformation and perception of news source reliability in secondary school students. *Discover Education, 3*(1), Article 93. https://doi.org/10.1007/s44217-024-00194-8

Siersma, P. T., Pol, H. J., Van Joolingen, W. R., & Visscher, A. J. (2021). Pre-university students' conceptions regarding radiation and radioactivity in a medical context. *International Journal of Science Education, 43*(2), 179–196. https://doi.org/10.1080/09500693.2020.1864504

Silva, G. P. S., & Trindade, N. M. (2022). Panorama and perspectives of the teaching of radiation and radioactivity at the high school level. *Science Education International, 33*(2), 224–231. https://doi.org/10.33828/sei.v33.i2.10

Sinclair, I. (2011). How traditional radio works. In *Electronics simplified* (pp. 95–117). Elsevier. https://doi.org/10.1016/B978-0-08-097063-9.10006-8

Singh, R. K., McCoubrie, P., Burney, K., & Ash Miles, J. (2008). Teaching medical students about radiation protection–What do they need to know? *Clinical Radiology, 63*(12), 1344–1349. https://doi.org/10.1016/j.crad.2008.06.010

Sitmukhambetov, S., Dinh, B., Lai, Y., Banigan, E. J., Pan, Z., Jia, X., & Chi, Y. (2023). Development and implementation of a metaphase DNA model for ionizing radiation induced DNA damage calculation. *Physics in Medicine & Biology, 68*(1), Article 014001. https://doi.org/10.1088/1361-6560/aca5ea

Soltani, A., & Askarizadeh, G. (2021). How students' conceptions of learning science are related to their motivational beliefs and self-regulation. *Learning and Motivation, 73*, Article 101707. https://doi.org/10.1016/j.lmot.2021.101707

Stevens, R., Machiyama, K., Mavodza, C. V., & Doyle, A. M. (2023). Misconceptions, misinformation, and misperceptions: A case for removing the "mis-" when discussing contraceptive beliefs. *Studies in Family Planning, 54*(1), 309–321. https://doi.org/10.1111/sifp.12232

Suzuki, T. (2012). The misconceptions on radiation and radioactivity. *Latin-American Journal of Physics Education, 6*, 75–77.

Talapko, J., Talapko, D., Katalinić, D., Kotris, I., Erić, I., Belić, D., Vasilj Mihaljević, M., Vasilj, A., Erić, S., Flam, J., Bekić, S., Matić, S., & Škrlec, I. (2024). Health effects of ionizing radiation on the human body. *Medicina, 60*(4), Article 653. https://doi.org/10.3390/medicina60040653

Tang, X., Yang, T., Yu, D., Xiong, H., & Zhang, S. (2024). Current insights and future perspectives of ultraviolet radiation (UV) exposure: Friends and foes to the skin and beyond the skin. *Environment International, 185*, Article 108535. https://doi.org/10.1016/j.envint.2024.108535

Taşlidere, E. (2021). Relative effectiveness of conceptual change texts with concept cartoons and 5e learning model with simulation activities on pre-service teachers' conceptual understanding of waves. *Participatory Educational Research, 8*(4), 215–238. https://doi.org/10.17275/per.21.87.8.4

Taylor, S. C., Alexis, A. F., Armstrong, A. W., Chiesa Fuxench, Z. C., & Lim, H. W. (2022). Misconceptions of photoprotection in skin of color. *Journal of the American Academy of Dermatology, 86*(3), S9–S17. https://doi.org/10.1016/j.jaad.2021.12.020

Thi Phuoc Van, N., Tang, L., Demir, V., Hasan, S. F., Duc Minh, N., & Mukhopadhyay, S. (2019). Review-microwave radar sensing systems for search and rescue purposes. *Sensors, 19*(13), Article 2879. https://doi.org/10.3390/s19132879

Thill, A., Cammaerts, M.-C., & Balmori, A. (2023). Biological effects of electromagnetic fields on insects: A systematic review and meta-analysis. *Reviews on Environmental Health.* https://doi.org/10.1515/reveh-2023-0072

Tsai, C. H., Eghdam, A., Davoody, N., Wright, G., Flowerday, S., & Koch, S. (2020). Effects of electronic health record implementation and barriers to adoption and use: A scoping review and qualitative analysis of the content. *Life, 10*(12), Article 327. https://doi.org/10.3390/life10120327

Tuieng, R. J., Cartmell, S. H., Kirwan, C. C., & Sherratt, M. J. (2021). The effects of ionising and non-ionising electromagnetic radiation on extracellular matrix proteins. *Cells, 10*(11), Article 3041. https://doi.org/10.3390/cells10113041

Turiman, P., Omar, J., Daud, A. M., & Osman, K. (2012). Fostering the 21st century skills through scientific literacy and science process skills. *Procedia-Social and Behavioral Sciences, 59*, 110–116. https://doi.org/10.1016/j.sbspro.2012.09.253

Tuttle, M. J., Cejas, D., Kang, D., Muchaamba, F., Goncarovs, B., Ozakman, Y., Aziz, F., & Orelle, A. (2023). Promoting science literacy and awareness across the globe: The role of scientists as science ambassadors. *Journal of Microbiology & Biology Education, 24*(2), Article e00041-23. https://doi.org/10.1128/jmbe.00041-23

Ugweje, O. C. (2004). Radio frequency and wireless communications. In H. Bidgoli (Ed.), *The Internet encyclopedia* (1st ed.). Wiley. https://doi.org/10.1002/047148296X.tie151

Ürek, H. (2021). Awareness of Turkish pre-service teachers about the risks of electromagnetic radiation in daily life cases. *Journal of Science Learning, 4*(2), 140–150.

Uzorka, A., Namara, S., & Olaniyan, A. O. (2023). Modern technology adoption and professional development of lecturers. *Education and Information Technologies, 28*(11), 14693–14719. https://doi.org/10.1007/s10639-023-11790-w

Valladares, L. (2021). Scientific literacy and social transformation. *Science & Education, 30*(3), 557–587. https://doi.org/10.1007/s11191-021-00205-2

Ventista, O. M., & Brown, C. (2023). Teachers' professional learning and its impact on students' learning outcomes: Findings from a systematic review. *Social Sciences & Humanities Open, 8*(1), Article 100565. https://doi.org/10.1016/j.ssaho.2023.100565

Vettenranta, S. (1996). The media's reception of the risk associated with radioactive disasters. *Radiation Protection Dosimetry, 68*(3), 287–291. https://doi.org/10.1093/oxfordjournals.rpd.a031881

Vieira, R. M., & Tenreiro-Vieira, C. (2016). Fostering scientific literacy and critical thinking in elementary science education. *International Journal of Science and Mathematics Education, 14*(4), 659–680. https://doi.org/10.1007/s10763-014-9605-2

Vila, A., Sánchez-Reyes, A., Conill, C., Gispert, J. D., Trampal, C., Láinez, C., Vayreda, J., & Pedro, A. (2010). Comparison of positron emission tomography (PET) and computed tomography (CT) for better target volume definition in radiation therapy planning. *Clinical and Translational Oncology, 12*(5), 367–373. https://doi.org/10.1007/s12094-010-0518-4

Vollmer, M. (2004). Physics of the microwave oven. *Physics Education, 39*(1), 74–81. https://doi.org/10.1088/0031-9120/39/1/006

Wang, E., Liu, X., Li, Z., Liu, Z., & He, X. (2014). Application of electromagnetic radiation (EMR) technology in monitoring and warning of coal and rock dynamic disasters. In C. Drebenstedt, & R. Singhal (Eds.), *Mine planning and equipment selection* (pp. 561–568). Springer. https://doi.org/10.1007/978-3-319-02678-7_54

Wang, S., & Zhao, J. (2022). New prospectives on light adaptation of visual system research with the emerging knowledge on non-image-forming effect. *Frontiers in Built Environment, 8*. https://doi.org/10.3389/fbuil.2022.1019460

Welbourne, D. J., Claridge, A. W., Paull, D. J., & Lambert, A. (2016). How do passive infrared triggered camera traps operate and why does it matter? Breaking down common misconceptions. *Remote Sensing in Ecology and Conservation, 2*(2), 77–83. https://doi.org/10.1002/rse2.20

WHO. (2014). Electromagnetic fields and public health: Mobile phones. *World Health Organization*. https://www.who.int/news-room/q-a-detail/electromagnetic-fields-and-public-health-mobile-phones

WHO. (2023). Ionizing radiation and health effects. *World Health Organization*. https://www.who.int/news-room/fact-sheets/detail/ionizing-radiation-and-health-effects

Williams, S. L. (1988). Addressing misconceptions about phobia, anxiety, and self-efficacy: A reply to Marks. *Journal of Anxiety Disorders, 2*(3), 277–289. https://doi.org/10.1016/0887-6185(88)90007-2

Wilson, J. R. (2019). Perception versus radioactive reality: How misconception influences radiation policy. *IEEE Potentials, 38*(4), 42–47. https://doi.org/10.1109/MPOT.2018.2857860

Wojcik, A., Hamza, K., Lundegård, I., Enghag, M., Haglund, K., Arvanitis, L., & Schenk, L. (2019). Educating about radiation risks in high schools: Towards improved public understanding of the complexity of low-dose radiation health effects. *Radiation and Environmental Biophysics, 58*(1), 13–20. https://doi.org/10.1007/s00411-018-0763-4

Wolfe, C. M., & Cognetta, A. B. (2016). Radiation therapy (RT) for nonmelanoma skin cancer (NMSC), a cost comparison: Clarifying misconceptions. *Journal of the American Academy of Dermatology, 75*(3), 654–655. https://doi.org/10.1016/j.jaad.2016.01.035

Wong, D., Leong, T. K., Ravindran, S., & Lin, L. S. (2023). Students' alternative conceptions and risk perceptions of radiation and radioactivity. *The Physics Educator, 5*(2), Article 2350009. https://doi.org/10.1142/S2661339523500099

Wood, A. W., & Karipidis, K. (Eds.). (2017). *Non-ionizing radiation protection: Summary of research and policy options*. John Wiley & Sons. https://doi.org/10.1002/9781119284673

Wood, A., & Roy, C. (2017). Overview: The electromagnetic spectrum and nonionizing radiation. In A. W. Wood, & K. Karipidis (Eds.), *Non-ionizing radiation protection* (pp. 1–9). Wiley. https://doi.org/10.1002/9781119284673.ch1

Xiao, C., He, N., Liu, Y., Wang, Y., & Liu, Q. (2020). Research progress on biodosimeters of ionizing radiation damage. *Radiation Medicine and Protection, 1*(3), 127–132. https://doi.org/10.1016/j.radmp.2020.06.002

Yamamoto, S., Watabe, H., Nakanishi, K., Yabe, T., Yamaguchi, M., Kawachi, N., Kamada, K., Yoshikawa, A., Islam, M. R., Miyake, M., Tanaka, K. S., & Kataoka, J. (2023). Hybrid imaging of prompt X-rays and induced positrons using a pinhole gamma camera during and after irradiation of protons. *Physics in Medicine & Biology, 68*(11), Article 115015. https://doi.org/10.1088/1361-6560/acd2a2

Yan, Q., Xin, B., & Liu, Y. (2021). Development and application of infrared radiation materials in the field of textile and clothing. *Journal of Physics: Conference Series, 1790*, Article 012054. https://doi.org/10.1088/1742-6596/1790/1/012054

Yan, S. (2024). Research on the applications of the wireless communication. *Applied and Computational Engineering, 40*(1), 192–198. https://doi.org/10.54254/2755-2721/40/20230649

Yin, S., Song, D., Li, J., He, X., Qiu, L., Lou, Q., Wei, M., & Liu, Y. (2022). Research on electromagnetic radiation (EMR) waveform characteristics of coal failure process using Hilbert-Huang transform (HHT). *Measurement, 187*, Article 110195. https://doi.org/10.1016/j.measurement.2021.110195

Zafar, U., Khattak, M., Zafar, H., & Rehman, H. (2022). Let's play games: A comparison of case-based learning approach with gamification technique. *Cureus, 14*(8), Aricle e27612. https://doi.org/10.7759/cureus.27612

ZafarAhmed, D., & ZafarAhmed, Q.-A. (2014). Health risks caused by wireless technologies. *Journal of Undergraduate Research at Minnesota State University, Mankato, 3*(1). https://doi.org/10.56816/2378-6949.1178

Zeleke, B. M., Brzozek, C., Bhatt, C. R., Abramson, M. J., Freudenstein, F., Croft, R. J., Wiedemann, P., & Benke, G. (2021). Wi-Fi related radiofrequency electromagnetic fields (RF-EMF): A pilot experimental study of personal exposure and risk perception. *Journal of Environmental Health Science and Engineering, 19*(1), 671–680. https://doi.org/10.1007/s40201-021-00636-7

Zloklikovits, S., & Hopf, M. (2021). Evaluating key ideas for teaching electromagnetic radiation. *Journal of Physics: Conference Series, 1929*, Article 012063. https://doi.org/10.1088/1742-6596/1929/1/012063

Zucker, A., Noyce, P., & Mccullough, A. (2020). Just say no! : Teaching students to resist scientific misinformation. *The Science Teacher, 87*(5), 24–29. https://doi.org/10.2505/4/tst20_087_05_24

Zwinkels, J. (2014). Light, electromagnetic spectrum. In R. Luo (Ed.), *Encyclopedia of color science and technology* (pp. 1–8). Springer. https://doi.org/10.1007/978-3-642-27851-8_204-1

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