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Review

Light Field Visualization for Training and Education: A Review

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Abstract: Three-dimensional visualization technologies such as stereoscopic 3D, virtual reality, and augmented reality have already emerged in training and education; however, light field displays are yet to be introduced in such contexts. In this paper, we characterize light field visualization as a potential candidate for the future of training and education, and compare it to other state-of-the-art 3D technologies. We separately address preschool and elementary school education, middle and high school education, higher education, and specialized training, and assess the suitability of light field displays for these utilization contexts via key performance indicators. This paper exhibits various examples for education, and highlights the differences in terms of display requirements and characteristics. Additionally, our contribution analyzes the scientific-literature-related trends of the past 20 years for 3D technologies, and the past 5 years for the level of education. While the acquired data indicates that light field is still lacking in the context of education, general research on the visualization technology is steadily rising. Finally, we specify a number of future research directions that shall contribute to the emergence of light field visualization for training and education.

Keywords: light field; light field display; 3D visualization; education; key performance indicator

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1. Introduction

Education is among the most important services provided to society. Its primary mission in the context of formal education is to transmit skills and knowledge. As technology evolved, so did the toolkit of education, as novel technological solutions gradually became integrated into the field of learning. In our current era, this is no different; in fact, the accelerated emergence of new technologies also results in the accelerated expansion of the set of devices and systems at the disposal of education institutions.

Among the different relevant technologies, electronic visualization systems have played an essential role in education since the early days of their emergence. In the 1930s, overhead projectors were introduced in schools, and by the end of the decade, in 1939, the first television was installed in a classroom. Today, novel digital visualization technologies are continuously being integrated into education [1–5], including 3D visualization technologies such as stereoscopic 3D (S3D), virtual reality (VR), and augmented reality (AR). The progress at which such devices are added depends on the country or region, the type of the institution (i.e., public or private), the level of education (e.g., higher education), and many other factors [6–9].

One common property of these 3D visualization technologies is that they have already emerged on the consumer market, and thus consumer-grade devices are available. This fact on its own may limit the expenses of introducing such technologies to education. However, these statements are not yet applicable to light field (LF) visualization—light field displays (LFDs) can be found only in a very limited number of higher education institutions, and it is currently a rather expensive technology in general.

In this paper, we review state-of-the-art 3D visualization technologies for training and education, and characterize LFDs as highly potential candidates for future education. We separately address the different levels of education (i.e., preschool and elementary school education, middle and high school education, and higher education), as well as specialized training. Beyond the technical analysis of the relevant key performance indicators (KPIs) [10], we approach the different contexts via use cases and specific utilization examples. The aim of this review is to assist paving the road towards the successful deployment of LF visualization technology in the various contexts of education. The considerations addressed by this paper are relevant for the construction of future research hypotheses and the design of the efforts of research and development. Additionally, the paper highlights the associated technological trade-offs, as well as the choice of universal and dedicated LFDs.

A major motivation of this paper is the lack of LF visualization in the scientific literature within the context of education—particularly in contrast to other technologies. Figures 1 and 2 exhibit the research and publication trends of the past 20 years in terms of yearly number and distribution, respectively. The evident dominance of VR is shown in both figures. The figures also highlight the gradual increase in AR articles and reviews, as well as the comparative decline of S3D since 2019. Regarding LF visualization, according to the Web of Science (WoS), only 10 articles have even remotely addressed LF in the context of education thus far. At the same time, the corresponding numbers for S3D, VR, and AR are 229, 5318, and 2586, respectively.

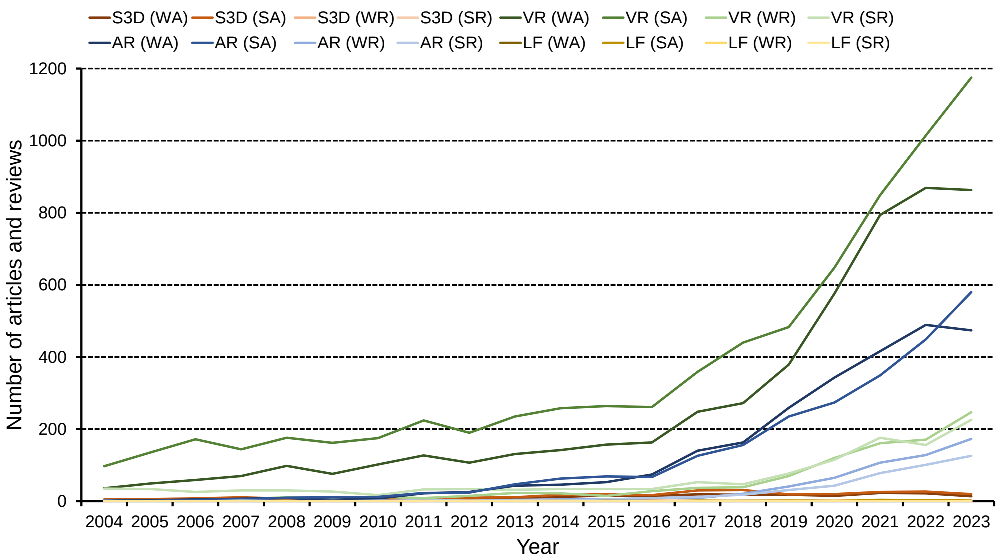

Figure 1. Number of articles (A) and reviews (R) in WoS (W) and SCOPUS (S) for 3D visualization technologies in the context of education in the past 20 years.

Figure 3 introduces the keywords used to search the WoS and SCOPUS databases. We addressed all four 3D visualization technologies for the three major levels of education. During the literature review, we approached relevance and impact from the perspective of citations. Additionally, we included a handful of works with lower citation numbers to enhance the topical balance of the review and to exhibit the topical diversity of the investigated fields. Moreover, in the data analysis, we excluded specialized training, as its addition may greatly overlap with higher education, creating redundancies—and thus, exaggerated results. We separately addressed the past 20 years (as shown in Figures 1 and 2), as well as the past 5 years—the latter in more detail.

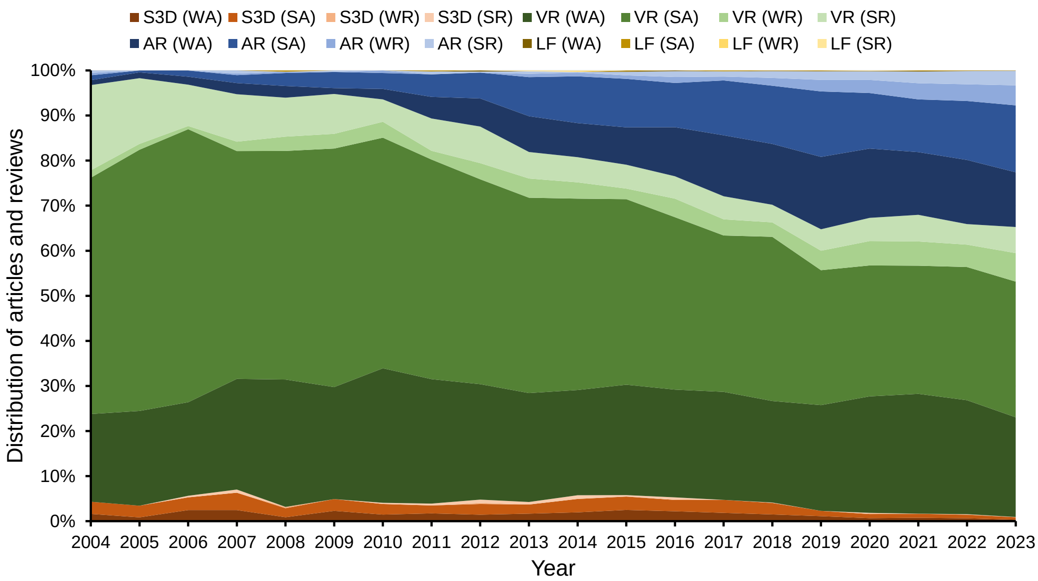

Figure 2. Distribution of articles (A) and reviews (R) in WoS (W) and SCOPUS (S) for 3D visualization technologies in the context of education in the past 20 years.

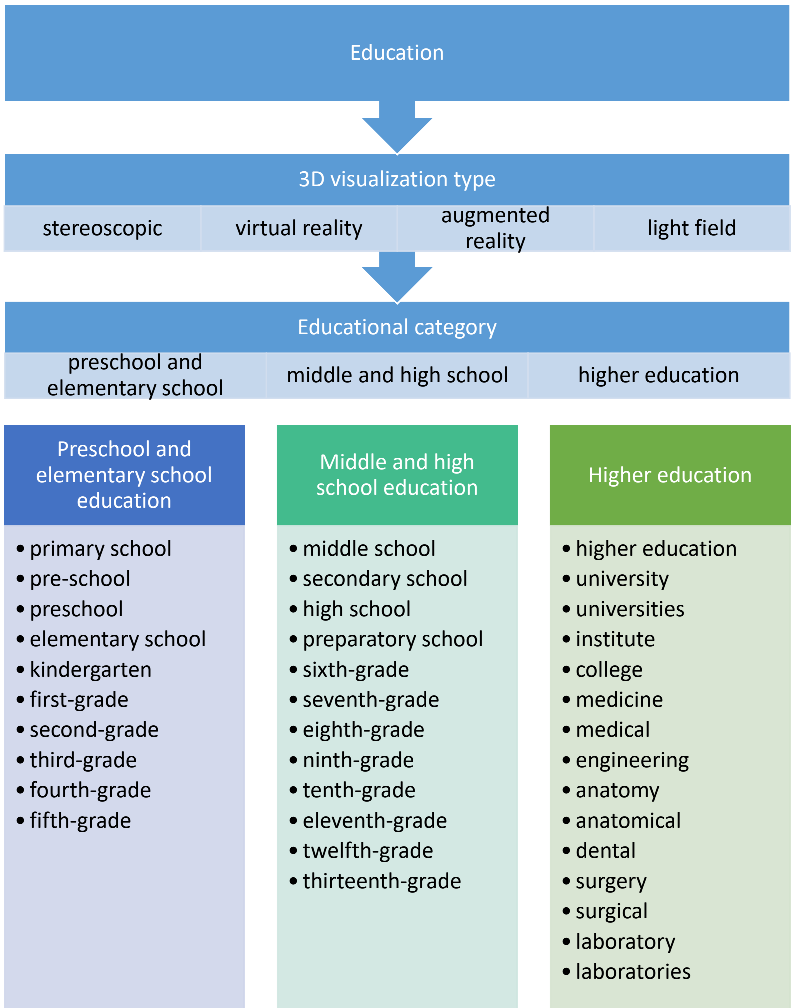

Figure 3. Combination of keywords for database analyses.

A notable limitation of this work is inherent from the limitations of the state-of-the-art scientific literature. In essence, one may find it challenging to review something that is yet to exist. However, the underinvestigated nature of LF in the context of education does not imply that LF in general is underinvestigated. This fact is additionally emphasized by the paper, along with the numerous future research efforts that are needed within and outside the topic of education. Another limiting factor of this work is the fact that as the primary focus is on LF visualization in the various types of training and education, the paper does not provide a fully comprehensive review of other 3D technologies in such utilization contexts. This is an intentional design of the contribution, as aiming for such an ambitious goal would not only disturb the topical balance and focus, but it would also greatly increase the total length of this work. Additionally, the other 3D technologies have already been very comprehensively reviewed for training and education. For example, the recent review of Marougkas et al. [11] addresses VR in education for the last decade. While other 3D technologies are briefly reviewed as well, our work mainly addresses LF visualization for training and education, the fact of which is reflected by the title of the paper.

The remainder of this paper is structured as follows. Section 2 reviews the considered 3D visualization technologies—namely S3D, VR, AR, and glasses-free 3D (including LF)—and analyzes the past 5 years of the scientific literature. Sections 3–6 address preschool and elementary school education, middle and high school education, higher education, and specialized training, respectively. Section 7 concludes the paper and highlights future work.

2. Considered 3D Visualization Technologies

2.1. Stereoscopic 3D

The term "Stereopsis" is derived from the Greek "stereós" and "ópsis", meaning "solid" and "power of sight", respectively [12]. Stereopsis is based on binocular disparity and binocular cues. S3D displays are built on the concept of stereopsis—two 2D images represent the content simultaneously from two similar yet different perspectives (analogous to the human eyes), and a viewing apparatus (e.g., 3D glasses) allocates one image to each eye, generating the perception of depth [12,13]. Based on the apparatus, one of the following approaches could be used to deliver these images to the eyes of the observer: (i) color multiplexing, (ii) polarization multiplexing, or (iii) time multiplexing. A common example for color multiplexing is the utilization of anaglyph images, where both the left and right images are combined by means of a complementary color coding method. Although plausible results may be achieved via anaglyph glasses, there is a possibility for losing color information, as well as being affected by crosstalk (i.e., interference). To overcome the aforementioned problems, a multitude of solutions were suggested, including adjusting the depth map, aligning images, and blurring color component [14,15]. An example for a color-multiplexed approach is the ColorCode 3D technique—commonly used in movies and video games—generating full-color images while working with standard hardware at lower costs [16]. In the case of polarization multiplexing, for a stereo image pair, each image has its light's state of polarization (SOP) mutually orthogonal. Such solutions rely on visual gears with polarizers, aiming to block the image not intended for the given eye. Taking advantage of the fact that the human visual system (HVS) is persistent in achieving 3D perception, time multiplexing alternates the displayed images intended for the eyes at a high frame rate (e.g., 120 Hz). For this kind of stereopsis, active shutter glasses are needed, in addition to being synchronized with the displayed content. Although this approach has proven its efficiency [17–19], cost remains an issue for the shutter glasses, as well as the need for excess video bandwidth.

Utilizing 3D stereoscopy in education can effectively enhance the learning process [20], conceptualizing abstract information in 3D models for better visualization, especially in the field of science [21]. The use of 3D models in the learning process can aid the focus of students on specific details, while also encouraging them to ask new questions [22]. Additionally, numerous works conclude that S3D may enhance student engagement in classrooms, supporting skills of discussion and writing [20,23,24]. Moreover, specialeducation students may also greatly benefit from using S3D visualization [23]. According to the scientific literature, S3D can be integrated in many training- and education-related tasks, including, but not limited to, spatial comprehension for complex structures and scenes, manipulation of real and virtual elements, as well as navigation. The work of McIntire et al. [13] concludes that in comparison to conventional 2D displays, S3D exhibited better spatial understanding of complex scenes (by 77%) and better performance when manipulating objects in a scene (by 67%). On the other hand, for tasks that do not depend extensively on depth information, S3D was proven to be similar or even worse in terms of performance. Medical education and training is an essential use case of state-of-the-art stereoscopy [25], where diagnostics may significantly outperform monocular cues [26]. Generally, S3D visualization of the human anatomy is greatly advantageous [27–30]. On the other hand, the crucial need for visual gears can be an obstacle, along with the possibility of 3D misperception [26].

2.2. Virtual Reality

VR is defined as immersive 3D environments that are virtually generated by computers. These are usually interactive environments, incorporating multiple sensory channels (e.g., position, touch, etc.). Navigation of the generated environments may also be possible, which is crucial for real-time simulations [9,31,32]. With such potentials and advantages, VR has been incorporated in various fields, such as tourism, medicine, military, sports, physical education, virtual stores, training and education, and many more.

Deploying VR for the context of training and education has proven to be beneficial with many perks compared to its conventional counterparts, including the aspects of safety, time-efficiency, and considerably low budget [33,34]. A notable example of the many advantages is that, instead of performing dangerous and/or expensive experiments in classrooms, VR can be used to perform the same while adhering to the safety measures in a budget-friendly manner [9]. Considering classrooms, VR may achieve sustainability, since updating laboratories (i.e., introducing new equipment) is not an issue [35]. The utilization of VR in education may significantly increase the cognitive skills of students in understanding complex concepts and structures [36]. Additionally, using eye tracking may assist the detection of distracted and confused students. This may also compensate the lacking interactions between the teacher and students in VR use cases. In their work, Rahman et al. [37] introduced six methods of gaze visualization for the teacher's VR view. These methods include gaze ring, gaze disk, gaze arrow, gaze trail, gaze trail with arrows, and gaze heatmap. Thanyadit et al. [38] proposed a visualization system called ObserVAR for observing and visualizing the gaze of students. The resulting visualization of the proposed system can be scaled up with the increase in the number of users, providing the teacher with a more comprehensive awareness of the virtual environment. Regarding training, similarly to S3D, the medical field has benefited greatly from the introduction of VR, since critical operations can be trained for without the need of exposing patients to potential danger. Due to its importance, a number of studies were carried out to analyze and assess VR in the medical field [39–41].

2.3. Augmented Reality

Unlike VR—which provides a complete 3D environment—AR generates only the overlays (i.e., virtual imagery information) over real environments, with the possibility of doing so in real time [42–44]. This capability of combining computer-generated visuals together with real environments made AR a viable tool for training and education. The work of Azuma et al. [42,45] summarizes AR via three criteria: (i) it is a combination of both real and virtual components, (ii) real-time interactions are allowed, and (iii) registration is in 3D.

Similarly to S3D and VR, AR has been primarily integrated in the education of the medical field. It was introduced in the first International Conference for Computer Vision and Virtual Reality (France, 1995), where head-mounted displays (HMDs) were used for teaching 3D anatomy, with human bone structures being overlaid on the real anatomical counterparts [46]. Considering the years between 1995 and 2009, 80 AR articles in education were documented by the WoS [47]. However, it is noted that the AR technology at that time was hardware-based, meaning that it was exclusively based on HMDs, heads-up displays (HUDs), and handheld displays. The solutions were expensive, and their usage was limited to the fields of healthcare, natural sciences, and engineering [48]. The year 2010 is regarded as a milestone year in AR, where libraries, software development kits (SDKs), and game engines were developed and utilized in the improvement and advancement of AR applications [47,49]. This facilitated the content creation for AR, in addition to the availability of smartphones—hence, drastically reducing the costs compared to the previous years. Additionally, in 2011, a major educational AR SDK called "Vuforia" was released [50]. Summa summarum, AR in the field of education was greatly enhanced in the last decade in all educational fields, spanning all levels of education [51]. In essence, it can be said that the last decade shifted focus from hardware-based solutions to application-based solutions for AR. Since 2020, novel dedicated AR devices were introduced for education—as well as for other types of utilization—such as smartglasses and Web-based AR, in addition to incorporating artificial intelligence (AI). This generation of AR has a lot of potential that needs to be investigated thoroughly. In the future, according to Garzón et al. [52], not only will the technical aspects of AR need to be considered when designing applications, but also the corresponding educational strategies and learning methods.

2.4. Glasses-Free 3D

In contrast to the previously detailed visualization technologies, glasses-free 3D displays do not require additional viewing gear. Among glasses-free 3D displays are the autostereoscopic displays, generating images with the needed disparity. They are autostereoscopic due to the fact that they provide different perspectives for the two eyes of the observer or user without relying on viewing devices. Such systems can be either two-view or multi-view displays. In the case of two-view autostereoscopic displays, a single stereo pair of parallax views is generated. The image pair can be generated either at a single location (for a single viewer) or in multiple points of space (for multiple viewers). In order to achieve stereoscopy, the viewer needs to be in the right position within the range of ideal distance from the screen. Two-view autostereoscopic display systems can be parallax-barrier-based or lenticular systems [19]. Regarding multi-view autostereoscopic displays, multiple stereo image pairs are generated for various locations (also known as "sweet spots") within the viewing area of the display. A major limitation for autostereoscopic devices is the location requirement of the spectators [53]. It should also be highlighted that the content is repeated over the different viewing locations; the same perspective is provided to each and every spectator. Other types of glasses-free 3D displays include volumetric and holographic displays. Volumetric displays generate volume-filling 3D visual representations, where light is emitted by voxels—located in 3D space—in the areas where they appear [54,55]. Volumetric displays have proven their efficiency in many fields, including medicine, military, and engineering [54]. Considering holographic displays, holography was introduced in 1948 by Dennis Gabor [56,57] (for which he was awarded the Nobel Prize in Physics in 1971); however, the generated holograms proved to be of poor quality. In order to enhance the holographic quality, various works were carried out [58,59], with the idea of digital holograms introduced in 1967 [60]. Later, in 1980, the fundamental theory for digital holography was proposed by Yaroslavskii and Merzlyakov [61].

Glasses-free 3D visualization comes with two evident advantages. First, of all, no viewing devices are necessary to view the visualized content—as the term "glasses-free" suggests. In contrast, the maximum number of simultaneous spectators in the case of S3D visualization is limited to the number of 3D glasses. Hence, the other major advantage is that multiple spectators may view the display in operation simultaneously. However, if we take multi-view displays, for instance, the different perspectives that one individual may perceive is very limited. Similarly to multi-view displays, LFDs provide a glasses-free 3D visual experience to multiple spectators simultaneously, with the important distinction that the display may use its entire field of view (FOV) to provide a single continuous parallax effect. It needs to be emphasized that FOV in this context is measured from the screen of the display, and not from the user's perspective (e.g., as in the case of VR). Moreover, any number of simultaneous viewers may be accommodated, as long as they can fit inside the valid viewing area (VVA), determined primarily by the FOV of the display. Among the most important KPIs of LF visualization are spatial resolution (which, if the content is generated from a series of 2D images, corresponds to their resolution), angular resolution (which is technically the density of distinct light rays), screen dimensions, depth (which is "depth budget" as a display attribute), brightness, and contrast, as well as FOV [10].

As glasses-free 3D displays allow multiple spectators simultaneously, they inherently support collaborative visualization experiences. Hence, they are rather convenient in multi-user scenarios, such as education in a classroom. On top of being glasses-free, their ability to convey depth accurately encourages their extensive utilization in a great number of fields and contexts, such as medical applications, including anatomy and diagnostics [62]. Regarding educational purposes, it should be taken into account that operation and maintenance for glasses-free 3D displays must be kept as simple as possible [63]. This is due to the fact that these displays are to be operated by teachers in classrooms, who do not necessarily have the sufficient expertise in 3D visualization technologies. Moreover, while such displays may offer notably better aspects of 3D visualization (e.g., natural depth perception), it was reported by children in the age range of 7 to 11 that frontal projections (i.e., 2D projection on a flat surface) are easier to use compared to autostereoscopic displays [64]. A relationship between age (four age groups) and visual comfort/discomfort (five levels of visual comfort) was also found [65]. The results indicate that older individuals tolerate autostereoscopic 3D visualization less, while children adapt more easily. Additionally, specifically for LFDs, it was shown that 2D displays may actually have better task completion times [66].

In the context of LF visualization, several different observer scenarios are possible, which are highly relevant to education. Figure 4 shows one scenario where multiple simultaneous observers use a given display system, and another one where there is only a single observer. In the former case, a wider FOV is required, particularly if the observers are mobile. In the latter case, a smaller FOV may be sufficient. However, even in the case of a single observer, a wider FOV may actually be necessary, as shown in Figure 5. The figure also exhibits a scenario with multiple simultaneous static observers. Note that the maximum number of simultaneous observers is limited by the accommodation capacity of the VVA, meaning that the observers must be inside the VVA in order to perceive valid LF visualization. In certain contexts, the angular resolution of the system and the content may be crucial for the VVA, as greater viewing distances result in the lower perceived angular density of light rays. According to the recommended practices regarding Quality of Experience (QoE) [67], the viewing distance threshold (i.e., beyond which visualization becomes more 2D than 3D; also known as recommended maximum viewing distance) for LF visualization can be calculated as

$$VDT = \frac{ID}{tan(AR)}, \tag{1}$$

where VDT is the viewing distance threshold, ID is the interpupillary distance (commonly measured as 6.5 cm), and AR is the angular resolution of visualization. This means that angular resolution on its own may fundamentally affect the use case in this regard. Evidently, screen size is also an important factor, and must be chosen in accordance with the use case.

At the time of writing this paper, the use case context of education is considerably underinvestigated for LF visualization. This is partially due to the fact that this technology has not yet entered the consumer market and, in fact, the availability of such displays to the scientific community is also limited. While some of our earlier works do consider education as a use case, they do not address the different levels of education and their characteristics. One of our works [68] provides recommendations on the viewing distance for LFDs. For this purpose, Equation (1) was extended by a use-case-dependent variable (p), resulting in

$$VDT = \frac{ID}{tan(AR)} \times p, \tag{2}$$

where the default value of p is 1. Smaller values bring the recommended maximum viewing distance closer to the screen, while greater values enable the opposite. For general education, a p interval between 0.8 and 1.5 was set, and for specialized training, this was constrained between 0.6 and 1. Our other work [69] covers use-case-specific quality degradations, which are highly relevant to education. Spatial resolution, angular resolution, depth budget, FOV, brightness, and contrast were considered for education, without distinguishing the different levels. In Sections 3–6, the three levels of education, as well as specialized training are addressed. The state-of-the-art 3D solutions of other technologies are also reviewed for each section.

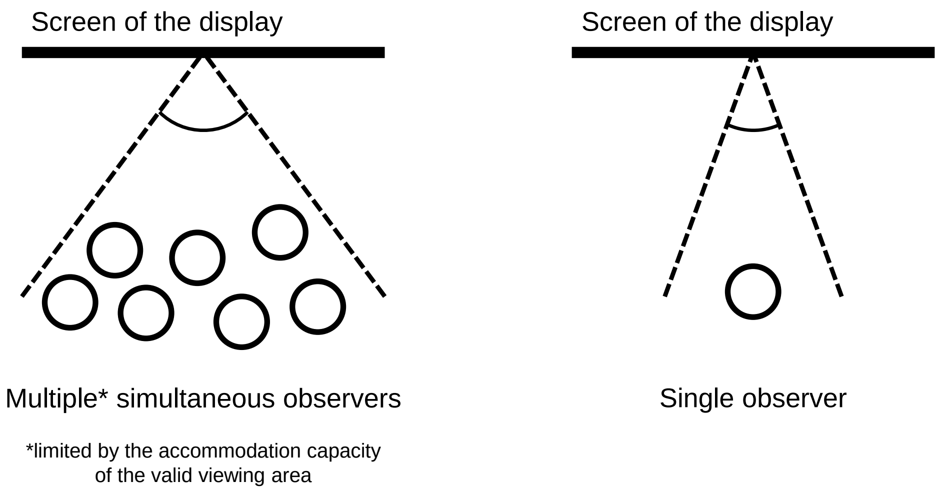

Figure 4. Light field visualization with a greater FOV for multiple simultaneous observers (**left**), and with a smaller FOV for a single observer (**right**).

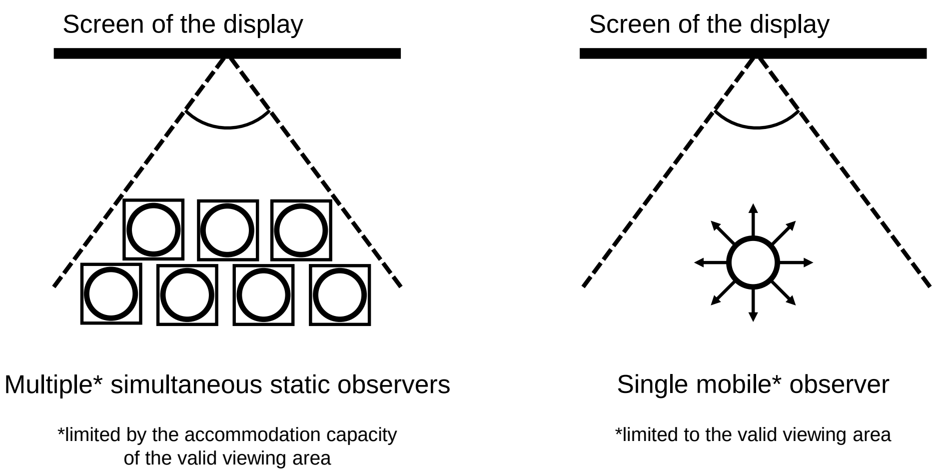

Figure 5. Light field visualization with a greater FOV for multiple simultaneous static observers (**left**), and with a greater FOV for a single mobile observer (**right**).

2.5. State of the Considered Technologies in Education

Figures 6 and 7 exhibit an analysis of the WoS and SCOPUS databases for 3D visualization technologies in the context of the different levels of education in the past 5 years. In contrast to the 20-year overview in Section 1, not only are the levels of education addressed, but glasses-free technologies are considered as well. They are denoted as GF in this analysis, and they exclude LF visualization.

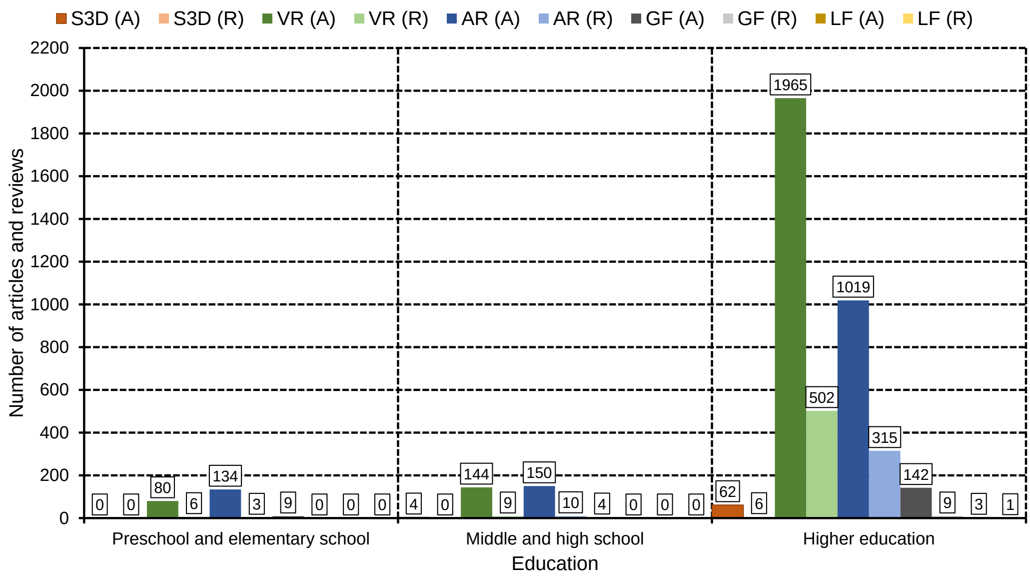

Figure 6. Number of articles (A) and reviews (R) in WoS for 3D visualization technologies in the context of education in the past 5 years.

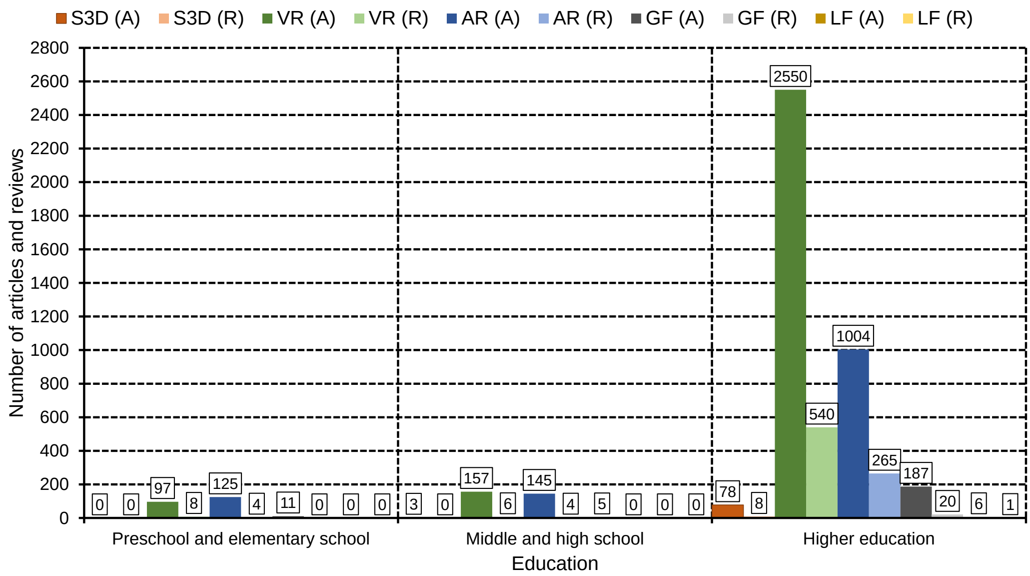

Figure 7. Number of articles (A) and reviews (R) in SCOPUS for 3D visualization technologies in the context of education in the past 5 years.

Similarly to the trends of Figures 1 and 2, VR has been dominant within this time frame as well, followed by AR. It should be highlighted that these recent works generally target higher education, while the earlier levels of education remain underinvestigated in comparison. Additionally, works on non-LF glasses-free 3D are also notable, particularly in comparison to S3D and LF. This observation is well in alignment with the decline of S3D portrayed by Figures 1 and 2. The analysis also shows that only a handful of research efforts on LF technology has been published in the context of education. Based on the searches in the two databases, a total of six articles and two review papers have been identified—the three articles registered by WoS are included in the six that are within SCOPUS, but the two reviews are different works.

However, even though these works do match our LF-related search criteria, they do not necessarily address higher education in a relevant aspect. For example, Salem et al. [70] proposed a learning-based method for LF image reconstruction. Their model was trained via raw LF images. Yet, it should be noted that while the work does contain keywords such as "education" and "university", they appear only in the affiliation of the authors. Luh et al. [71] proposed utilizing smartphone sensors for multiple experiments designed for teaching the fundamentals of physics. Beyond well-known sensors such as an accelerometer, the abstract of the work claims the usage of so-called "LF sensors"; however, the work clearly reports that those are, in fact, regular light sensors—hence, another false positive of this analysis. Shi et al. [72] introduced an LFD system composed of a projector and a view combiner. The work highlights the properties of the system, including the size of the display (20 inch), the vertical viewing angle (15.6 degrees), and the potential viewing distance (over 5 m). The authors proposed various applications for the LFD, which also includes education; however, it is merely mentioned in a single sentence.

In contrast, the work of Pan et al. [73] exhibits the usage of a Looking Glass LFD in a practical context of education. More precisely, the investigated collaborative learning scenario was sharing different veterinarian anatomy models among a student and a teacher simultaneously. A problem-based learning (PBL) approach was used in the vet tutorial, in which the student could interact with the visualized content. It is important to emphasize that the solution relies on dynamic viewing zones, enabled by user tracking. This was utilized for anti-cheat quiz support. Additionally, the system was assessed via an expert review, which resulted favorable feedback, highlighting the future potentials of such solutions.

It is imperative to clarify that the lack of education-related works for LF visualization does not mean that there is a lack of research efforts on LF technology. In fact, there is a steady increase in such contributions. Figure 8 shows the number of articles and review papers on LF in the past 20 years. The figure exhibits database values for general LF research (including, e.g., image compression and objective quality assessment), as well as works on LFDs (i.e., that either introduce novel systems or use existing ones). While the latter is still fairly limited, the number of the annual articles are roughly ten times of what there was 20 years ago. The continuous increase in the number of articles is particularly applicable to the past 10 years. Summa summarum, while education-related LF is still underinvestigated, LF, in general, is not.

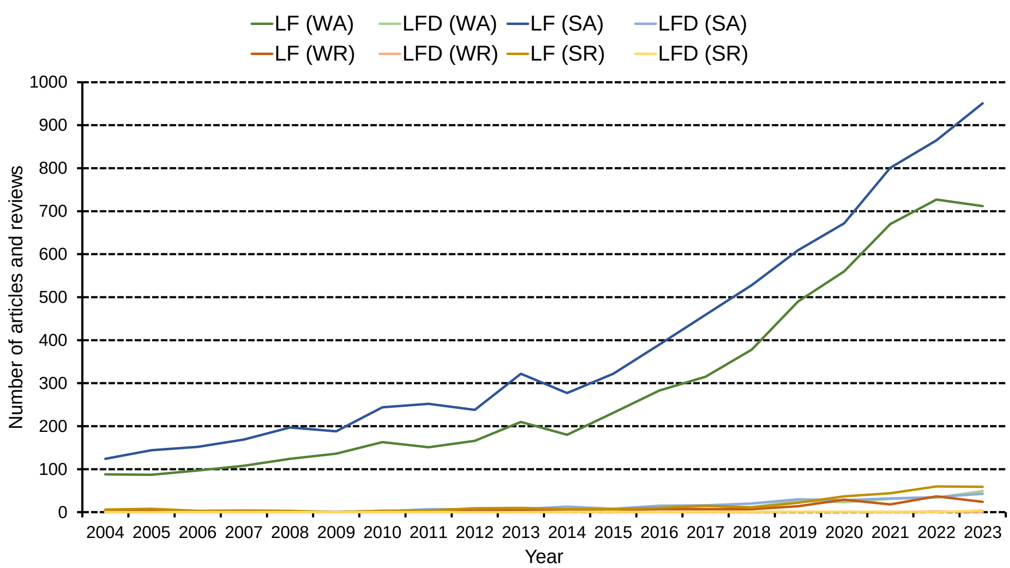

Figure 8. Number of articles (A) and reviews (R) on light field (LF) and light field display (LFD) in WoS (W) and SCOPUS (S) in the past 20 years.

3. Preschool and Elementary School Education

Effective learning in elementary schools is achieved by tailoring the learning process to the thinking capacity of students and uniqueness of the taught material. In their work, Permana et al. [20,74–76] studied the impact of integrating S3D images in textbooks, especially for science. This was experimented on two schools with a total of 52 forth grade students, where one school served as the experimental class with 26 students, and the other was the control class. The methodology allowed the experimental class to use the 3D material, whereas the control class followed the conventional textbooks. Pre- and post-tests were conducted on the mastery of the learning material, before and after the learning process. The results of the experimental classroom showed higher learning rates compared to the control classroom, indicating the effectiveness of using S3D images in the learning process. Furthermore, S3D displays can be used in the process of learning new languages, where vocabulary is crucial. A study was conducted to investigate the effect of using S3D in the vocabulary learning of the Polish language [24]. Moreover, a research effort targeting 5-year-old preschoolers was carried out to examine the effects of using interactive applications and 3D animated movies in developing their visual perception [77]. Taking advantage of the rapid development of 3D displays, the Ministry of National Education of Turkey deployed the Action to Increase Opportunity and Improve Technology (FATIH) project [78]. The scope of this project is to integrate IT in school lessons to enhance the teaching methods by addressing multiple sensory organs of students. This was achieved by creating a network infrastructure for all classrooms and for all grades—from preschool to high school—in addition to using LCD interactive boards (IBs). Based on both the available 3D technology at the time, and the properties of the utilized IBs, interactive 3D (I3D) educational materials were designed specifically for the IBs.

Although VR has proven its efficiency in the learning process, how to integrate it in elementary schools remains an open research question. Patterson and Han [79] interviewed a South Korean elementary school teacher about their journey in using VR in classroom. The interview details the means to integrate VR in teaching. VR has been integrated in a variety of subjects taught to preschoolers and elementary school students, including the study of VR effectiveness in science [80], art education (specifically 3D drawing [81]), natural sciences [82], mathematics [83,84], geology [85], and moral education [86]. An interesting utilization case of VR in elementary, as well as middle and high schools, is deployed in history classes. While history in itself is interesting to learn, adding virtual simulations of the architectural structures of the historical sites may greatly engage the students, since it is rather costly to travel around the world and experience history and cultural heritage in their native locations. Therefore, studies for virtually immersive field trips in elementary schools were conducted [87,88]. Shibata et al. [22] investigated the use of VR to study stone chambers and Haniwa from the Tumulus period in Japanese history. Gaitatzes et al. [89] implemented virtual simulations of certain Greek cultural heritage sites, while allowing participants to freely explore and interact with the scene contents. In addition to simulating and exploring existing sites, VR can be used to simulate ancient historical locations that no longer exist. This was established by Perez-Valle and Sagasti [90], who used VR to enable the exploration of Spain from the 16^{th} century, within which many locations and temples are lost to the ages.

Since the students of our era are highly engaged in the digital world, Freitas and Campos [91] implemented a system named the System of Augmented Reality for Teaching (SMART) for teaching second grade students. This system was tested in three schools, on 54 students in Portugal. The results indicate an increase in the motivation of students, enhancing their overall learning experience, especially for those who are academically lacking. Many studies were conducted to explore the utilization of AR in elementary schools, including the usage of AR to learn natural sciences [82], geometry [92], human anatomy [93], Bengali letters [94], fine arts [95], and science [96]. Another study was conducted in 40 schools in Indonesia to examine the effects of using AR to study science in elementary schools [97]. The results indicate the increase in student understanding, with better engagement in the science curriculum.

Unlike VR and AR devices—supporting a single student at a time—glasses-free 3D displays can adapt to multiple students at once. Zheng et al. [98] suggested the Mixed Reality Sharing Platform (METAL) for sharing educational material between the teacher (using a Microsoft HoloLens 2) and students (using Looking Glass displays) in a one-to-multi fashion. This platform allows the synchronization of educational materials. Xu et al. [63] suggested using simple autostereoscopic devices in classrooms for the sake of ease of operation and maintenance. Accordingly, the authors proposed a cost-efficient Interference Filter Technique (Infitec) 3D display system for elementary, middle and high schools. Instead of using high-end projectors for Infitec systems, the authors deployed two consumer-grade projectors for creating 3D visualization via filter interference. Taking the advantage of the popularity of video games among students, Fernando et al. [64] implemented an autostereoscopic system for educational purposes, where children (age range 7 to 11 years old) could see themselves within the game as a background while being able to interact with the 3D elements in the scene by means of Microsoft Kinect.

Considering this level of education, big screens accommodating to the potentially large numbers of students are preferred. In this case, the design of the LFD should take into account having a wide FOV with a large VVA (i.e., wide-baseline solutions), enabling multiple spectators at once. Smaller FOV values can be used for smaller classrooms with fewer students, but it is somewhat ineffective on a large learning scale. While the accuracy of the presented models is not an issue, vivid colors are required to grab the attention of students of that age. Taking into account the vibrant colors, in addition to the large dimensions of LFDs, appropriately large spatial resolutions (i.e., adequate for the screen size) should be considered to avoid blurriness. However, note that fully synthetic contents do not necessitate high spatial resolution [99,100]. Additionally, resolution values may impact students with reduced visual capabilities differently, fundamentally depending on the viewing distance [101].

Elementary education requirements for LFDs can be regarded somewhat similar to that of digital signage, but on a smaller scale. The main idea is to grab and maintain the attention of students with vivid colors and impressive depth values—i.e., depth in both directions, positive (away from the observer) as well as negative (towards the observer)—while having a big size screen. Depending on the presented content, angular resolution should be discussed. For instance, in the case of static viewing conditions (i.e., students are not moving around; e.g., as shown in Figure 5), angular resolution is not considered a significant issue [102], whereas in the case of mobile students, angular resolution plays a central role in the perceived quality of visualization. However, even in such a case, it does not have to be exceptionally high, as it simply affects the plausibility of the presented material, and it is not crucial to the effectiveness of the use case. Regarding the fact that currently LFDs are rather expensive, considerations related to student behavior should be taken into account, especially at such a young age. This also puts further obligations in presenting 3D content that is highly engaging. For this level of education, an LFD with adequate spatial and angular resolutions is sufficient, since the visualized content is usually simple. In addition to all the aforementioned properties, the LFDs targeted for classrooms should be easily maintained and operated, as it is meant to be used by teachers who are mostly not experts in state-of-the-art display technology.

In the context of preschool and elementary school education, it is rather likely that the rooms of the school are well illuminated by natural light. This means that brightness and contrast must be appropriate to handle the sunniest days. However, for projection-based LFDs, this is typically not an issue. As stated earlier, the use case is indeed somewhat similar to digital signage, also in the sense that the display must fulfill its fundamental role even in a bright environment.

Regarding LFD types, there are two aspects to consider. One is the parallax direction, and the other is projector location in the case of projection-based LFDs. The 3D experience is enabled by the parallax, the direction of which may be horizontal, vertical, or both. Analogous to this classification, LFDs may be horizontal-only parallax (HOP), vertical-only parallax (VOP), or full parallax (FP). The real world is best represented by FP solutions; however, such displays also necessitate more resources in terms of 3D data and its related actions (e.g., rendering, storage, transmission, etc.), and the display system is also expected to be significantly more complex and expensive. As the human eyes are horizontally separated, HOP displays can be considered suitable for most use cases. Additionally, the vast majority of potential movement in the context of education is horizontal as well (e.g., moving around the classroom), and not vertical. Regarding projection systems, the projectors may be on the same side of the screen as the observers (front-projection systems), or on the other side (back-projection systems). For the lowest level of education, back-projection systems are preferred, particularly since front-projection solutions may impose a restriction regarding the VVA, as being too close to the screen may occlude light rays, resulting in invalid LF.

Let us consider a case of elementary school education where students are allowed to move around the screen—within the VVA of course. It is possible to organize class activities in which student move from the left side of the VVA towards the right, as shown in Figure 9. The angularly selective nature of LFDs enables the visualization of progress. This means that the visualized content changes proportionally to the viewing angle. For example, the case of a caterpillar evolving into a butterfly can be illustrated, as shown in Figure 9.

Future use cases of LF in education should also take into consideration the psycho-physiological characteristics of students [103,104]. Such can be highly relevant for 3D visualization, including LFDs [105,106]. Regarding this specific level of education, the work of Yursinboevich [107] analyzes the psycho-physiological development of students during the learning process in general, and physical education classes in particular. In order to accommodate to preschoolers, a research was conducted to design a new paradigm targeted for each contemporary child's own abilities, taking into account their psycho-physiological structures [108]. Moreover, a study was designed to evaluate the psycho-physiological responses of elementary school students to visual stimuli consisting of foliage plants [109]. The work compared the impact of perceiving a photograph of a plant, an artificial plant, an actual plant, as well as the absence of a plant. The results indicate that an actual plant may improve attention and psychological relaxation. As the long-term goal of LF visualization is to pass the visual Turing test [110] (i.e., to provide a visualization that is indistinguishable from real life), the gap between real entities and their digital counterparts may be reduced, which may contribute to such contexts.

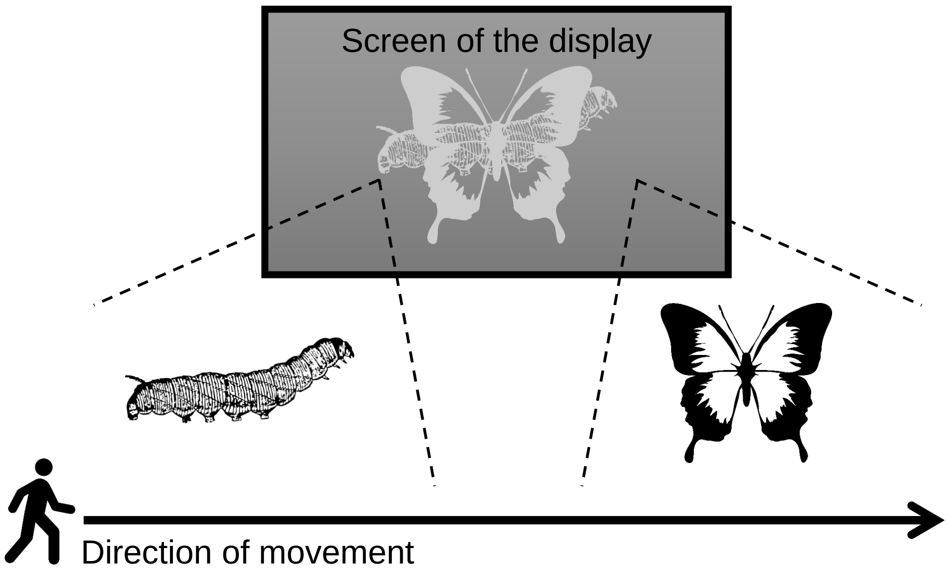

Figure 9. The life cycle of a caterpillar on an LFD.

4. Middle and High School Education

To point out the effects of using S3D for education, multiple studies were performed to compare the monocular 3D vision (i.e., 2D displays) and S3D displays for middle and high school students. A study performed by Remmele et al. [111] was conducted on 144 eighth grade students to study biology. The results showed that S3D visualization may greatly help the students in understanding the internal structure of the human nose. Another study was conducted by Taştı and Avcı [112] on 66 ninth grade students. The outcome of the work indicates that using animations on S3D displays provide better results in the engagement of students compared to conventional 2D displays.

As stated earlier, an advantage of virtual classrooms is that, unlike conventional classrooms where dangerous testing experiments pose a threat to students and expensive equipment is required, such virtual environments—experienced via VR—provide the possibility to perform the same in a hazard-free manner and without any equipment besides the VR gear [9,113]. Additionally, VR can be integrated in various subjects to enhance the learning experience for middle and high school students. This includes using VR to visualize geography in 3D to enhance the understanding of geographical structures [114]. Furthermore, VR can be used to simulate industrial robotic arms for high school and engineering students. In their work, Román-Ibáñez et al. [35] implemented a virtual environment to study the effect of trajectories designed by students on various robotic arms. In this simulation, collisions with the different scene objects were detected and notified to alert students. The experiment enhanced the understanding of robotics in a cost-efficient and safe manner, as there was no possibility for any health hazard or for any damage to occur.

Visualization is simply essential when it comes to teaching subjects such as geometry. The lack of imagination of some students (i.e., the inability to mentally visualize mathematical shapes and objects) can hinder the learning of such subjects. Accordingly, AR can be used to teach geometry by displaying the 3D models for better understanding and mental visualization. Chang et al. [115] designed an application called "Construct3D", displaying 3D geometric models while enabling users to construct these models via HMDs. Moreover, these models can be overlayed onto the real world. Furthermore, AR can be utilized to teach the properties of dynamic differential kinematics [116]. Attempts included the utilization of AR to present an element dynamically when varying in time (e.g., velocity and acceleration) [117], and physics simulations [118].

While 2D media is less suitable in terms of visualizing complex structures (e.g., molecules), autostereoscopic displays can solve this issue. Accordingly, they can be used in chemistry education by modeling the molecules accurately with appropriate depth and parallax [119]. Additionally, an autostereoscopic display and an interactive panel was used for visualizing solid shapes generated by computer graphics, while providing the means of interaction with the presented shapes to allow modifying their features (e.g., translation, rotation, scaling, and cutting) [120].

Whereas high school education mostly requires the same LFD specifications as elementary school, higher angular resolution may be necessary. The presented materials for students at this age range are expected to be more complex, such is the case in science classes with basic anatomy presented, history, geography, chemistry, complex mathematical models, and other subjects. Accordingly, not only do we need to consider the spatial resolution, but the angular resolution as well, especially in the case of complex structures.

Among the different branches in geology is stratigraphy—the study of soil and rock layers, and layering in general (stratification). For better understanding of the different layers in soil, LFDs—specifically FP LFDs—can be used to exhibit the different layers of the soil over the years. This could be achieved by means of vertical parallax, where students can move up and down to check out the different layers constituting the land, as illustrated in Figure 10. However, as FP LFDs may be out of the scope of this level of education, the alternatives are to use either HOP or VOP displays. Yet, investing in a VOP display is not necessarily a cost-efficient decision, as the opportunities of utilization in this specific level of education may be severely limited. Therefore, a 90-degree rotation of the content may be the most reasonable, in order to enable compatibility with HOP solutions. Additionally, it may be inconvenient to efficiently use a VOP display in this context. Generally, students—or any type of observer—may better differentiate their horizontal viewing angles than the vertical ones. This may evidently limit the number of effectively-perceivable key perspectives along the vertical axis.

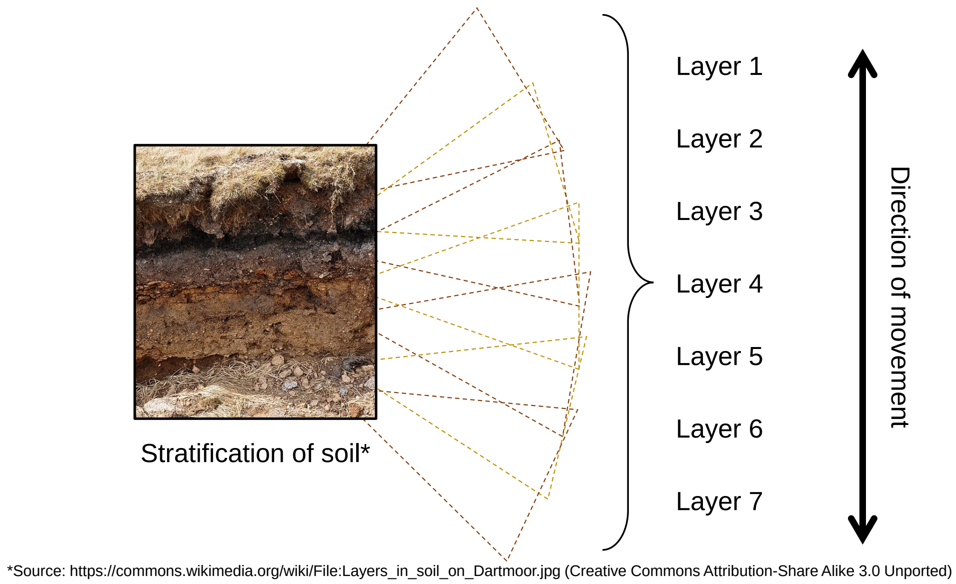

Figure 10. Using an LFD for studying stratification.

Since different perspectives of the visualized scene are presented to the spectators, depending on their position, LFDs can be used in education by means of serious gaming for in-class tasks and assignments. In this use-case scenario, the different perspectives may be used for increasing team work among students. For example, in the context of robotics, the 3D model of a robot can be visualized on an LFD with a defect in one of the parts. The team members would be placed in different locations around the screen, where each one needs to identify whether the defect part is in the given perspective of the visualized model. The team members are encouraged to explain their visualized part of the robot to one another, and brainstorm together to help each another reach the correct solution. Similarly, LFDs can be used in the case of anatomy for biology classes.

Serious games are not the only games that occur in high school education. While video games in elementary schools primarily serve educational and recreational purposes, high school students may already engage in e-sports [121,122]. However, based on the gaming genre, the players of competitive games may share a single perspective (e.g., fighting games). Yet, split-screen solutions are absent, as they allocate only a portion of the screen to a given player (e.g., horizontal division), and may compromise the competitive nature of the game by sharing player information. Instead, for such games, individual screens are assigned to the different players. This may be overcome by split-domain LF visualization, which allocates a specific portion of the VVA to the player [123,124]. While the example shown in Figure 9 is based on gradual change, such split-domain solutions change content—in this context, gaming perspective—without any transition. This also comes with the disadvantage that it creates invalid LFs between the zones of the segmented VVA due to content interference. It is important to note that any LFD may support split-domain LF visualization, as it is fully software based. Therefore, LFDs in high schools may enable split-domain gaming without dedicated hardware or any additional requirement. It is also possible to implement dynamic solutions via user tracking, such as the work of Pan et al. [125].

As high school students may spend more time with digital equipment than elementary school students, a research effort was designed to improve the psycho-physiological responses of high school students by introducing interventions with active stretching within the extended periods of using computers [126]. Regarding visually impaired students, a study was conducted to investigate their psycho-physiological problems, the results of which indicate positive correlations between visual impairments and psychological effects [127]. Visual impairments may have a fundamental impact on the perceived quality of LF visualization—as emphasized by the results of Simon et al. [101]—and thus may pose significant challenges regarding the effectiveness of educational use cases.

5. Higher Education

S3D can be used to simplify the learning process of complex structures and elements, among which is anatomy. Studies to examine the effectiveness of using S3D in learning anatomy includes the comparison between conventional 2D videos and 3D anaglyphic stereoscopic instruction videos in learning neuroanatomy [28,29]. Furthermore, to allow multiple students and trainees to share the learning experience, Deakyne et al. [128] augmented the anatomies viewed in VR onto an external display via a custom anaglyph shader, while presenting users with anaglyph glasses. Meta-analysis for using stereopsis with 3D visual technology (3DVT) to learn anatomy was conducted by Bogomolova et al. [30]. Stereo-pair image recording and generation for anatomy educational purposes was extensively performed in multiple efforts [129–132]. Considering textile and fashion studies, students are required to learn about textile chemicals in laboratories. An application was implemented on S3D displays for learning about textile chemistry in an interactive virtual environment before entering real laboratories [133]. Regarding engineering, anaglyph models can be used to illustrate complex 3D models encountered in production engineering [134]. Furthermore, exploiting the depth perception accuracy in S3D displays, such devices of 3D visualization could be used in product design education, where the perception of proportions and proportional relationships are crucial [135]. S3D visualization can be further used to simulate environments that are difficult or impossible to visit in real life. Such is the case of astronomy. However, by using VR, simulations of the Solar System and multiple galaxies can be visualized [136].

Regardless of the exact medical field, anatomy is crucial to learn and understand. It is involved in every single field of medicine—from a simple physical examination to a complex emergency procedure [137]. In their work, Falah et al. [40] considered using VR for better visualization when studying anatomy, to enable medical students to understand the 3D relations between the different structures, creating an engaging experience without the need for inadequate memorizing. Additionally, VR can be used to overcome the problem of limited cadavers when teaching medicine [40]. Another study focused on VR simulation of medical emergency crash carts targeted for nursing students [138]. Again, one of the advantages of VR is its ability to create different immersive experiences without the need to travel. This could be used in the area of wind energy education, where wind farms are virtually simulated. In this environment, users can change the various parameters related to wind farms and wind turbines, visualizing the resulting outcomes from such changes [139]. Additionally, construction field trips can be simulated using VR to increase construction safety education for university students prior to visiting real sites. In their work, Pham et al. [140] created a virtual environment by means of a 360-degree panoramic VR.

Applying AR in higher education can simplify the learning process, especially for complex systems, structures, and machinery. In their work, Liarokapis et al. [141] implemented an AR model of a camshaft, displayed along with real engine parts. The outcome highlighted the added value of using AR to ease the process of learning complex theories, with better learning results when adding interaction. Other complex structures to consider are molecules and atoms. Fjeld and Voegtli [142] suggested using AR for learning chemistry in what is known as augmented chemistry, displaying the constituting components of atoms and molecules. Still, the most potentially complex structures can be found in the field of anatomy. The conventional approach for anatomical education are cadaver dissection classes, providing 3D views of the anatomy of the human body. However, this may be a costly approach. Integrating AR in anatomical education allows for the 3D visualization of anatomical images, while adding real-time interactions, enhancing the sensory experience of the students. Various AR systems were developed in the field of anatomy education [143–150]. In a different work, Bogomolova et al. [151] studied the possibility of integrating 3D visualization in anatomical education by means of HoloLens worn by assessors and examinees, sharing the same AR model. The experiment included assessing anatomical knowledge in 10-minute sessions, with interactions between both the assessor and examinee in real time. The work of Cercenelli et al. [152] investigates the possibility of using AR along with 3D printing for anatomical education.

Due to the lack of the need for additional viewing devices in the case of glasses-free 3D displays, they can be considered the perfect candidate in medical education and training—as well as for many other use cases. Early works proposed holography in augmenting medical and anatomical education [153,154]. Several attempts for multi-view autostereoscopic display utilization in medicine were carried out, including the implementation of a software for interacting with 3D medical models in real time [155], the 3D visualization of real captured surgical videos [156], neurosurgical reviews [157], an educational application for head and neck anatomy [158], and interactive 3D torso anatomy [159]. In a recent attempt to use autostereoscopic displays, specifically the 8-inch Looking Glass Portrait display [160], King's College London (KCL) implemented an online platform, namely Virtual Anatomy and Histology (VAH), targeted for anatomical teaching by means of 3D visualization of medical models and medical scans [161]. Furthermore, Itamiya et al. [158] developed an autostereoscopic viewer that takes as input 2D CT, MRI, and CBCT images, and outputs the corresponding 3D model.

Regarding higher education, the budget for the educational entities are relatively more than that of elementary and high schools, not to mention that many universities have extensive budgets due to sponsorship. Hence, LFDs with better capabilities can be acquired. Since more targeted and complex subjects are taught in higher education, better spatial and angular resolutions are needed to visualize the learning material on LFDs. In other words, the more complex the presented structures, the higher the needed spatial and angular resolutions. For example, in the fields of mechanical and electrical engineering, numerous components may be highly detailed, and there may be significant variations in depth. While low spatial resolution may result blurred details, low angular resolution may degrade smaller elements to a point where they are no longer identifiable.

A major challenge to consider when using LFDs is that the region within which objects are rendered sharply is located around the plane of the screen. This challenge may affect the rendering of complex structures that needs to be scaled up considerably to view it more clearly (e.g., molecules). In previous works [162,163], we have acknowledged that using a first-person camera for LFDs result in deteriorated outputs. The same can be thought of when scaling objects. In that case, the region of interest (ROI) of the LFD should include the scaled part of the 3D model under visualization to achieve scaling while avoiding the blurry region. Considering the previous example of mechanical and electrical engineering, we need to highlight that content details that leave the plane of the screen the most (i.e., have the greatest depth) are the most susceptible to degradation, particularly to degradation caused by insufficient angular resolution.

Unlike the lower levels of education, higher education may actually have usage contexts for LFDs with smaller FOV values. This is due to the fact that a great number of educational instances may be viable without larger audiences (i.e., solo cases of specialized education). In other words, the FOV should primarily consider the use case itself and its visualized contents, instead of focusing on maximizing spectator accommodation. Moreover, while it is not expected that students of elementary and high school education would spend extended amounts of time using LFDs—apart from e-sports and similar competitive cases—it is more likely that the extensive training programs of higher education would result such. As students on their own or in groups may spend countless hours using LFDs to hone their skills and expertise in the given field, perceptual fatigue must be considered as well. However, at the time of writing this paper, the perceptual fatigue associated with LFDs has not yet been thoroughly investigated. The results that are available for laser-projection LF [164] suggest that such visualization is more exhaustive than conventional 2D displays.

As the institutions of higher education are typically equipped with different laboratories, lighting conditions should not pose a general issue. However, certain types of educational contents may require significantly better contrast values in order to support the accuracy of 3D visualization. This is particularly relevant for specialized displays (e.g., LF HUDs).

Regarding research on the psycho-physiological characteristics of students of this level of education, the implementation of an AI-based model to measure the psycho-physiological behavior of university students was introduced by Chahar et al. [165]. The work highlights the per-student customization of digital tutoring systems, as well as efforts towards the well-being of university students. Other notable studies include the impact of short, intensive physical stress in changing psycho-physiological parameters [166], and assessing the psycho-physiological responses of college students to plantscape colors (i.e., red, yellow, purple, white, and green) [167]. As colors may play an essential role in educational contexts, high dynamic range (HDR) visualization may be crucial to LF visualization [168,169]. This is generally applicable to all levels of education.

6. Specialized Training

Similarly to higher education, a multitude of works investigated the utilization of S3D in the field of medicine, especially surgery and anatomy. Earlier studies investigated the use of S3D in anatomy practical examinations [170] and evaluated the stereoacuity (3D vision) in practitioner surgeons [171]. However, one of the most notable use-case contexts that is not present in the different levels of education yet imperative to specialized training is the military. Works for using S3D in military include the investigation of the effectiveness of such devices for military training [172], their utilization for enhancing military driving [173], and understanding battlespaces and increasing situational awareness for military operations [174].

Since the last decade, VR has been integrated in various training applications such as flight simulations, particularly military flight simulations [175]. In the context of commercial flying, VR provides flight attendants with a training opportunity in case of aircraft fire drills with real-like hazards. This includes having virtual passengers around while simulating their different reactions, as well as their potential injuries [176]. Similarly to the idea of aircraft fire drills, Feng et al. [177] suggested implementing a serious immersive game in VR for the purpose of evacuation training. The idea is to present participants with the real environment in case of indoor evacuation emergencies while tracking their fear and anxiety levels by means of an electrodermal activity sensor. Furthermore, the blood volume level amplitude of the participants was measured via a photoplethysmography sensor. Finally, the emotional responses of the participants were measured by a multichannel physiological recorder when encountering fire emergencies. VR simulations also have great advantages in specialized surgical education, where surgeons can safely train outside the operation room (OR) on realistically interactive models of body organs [178–180]. In their work, Wang et al. [181] suggested using immersive VR in the field of construction engineering to improve the concentration of trainees, while giving them control over the environment. It was also suggested that it could be used further for education. One of the major goals in industrial manufacturing is to create products with minimum flaws. As a means to achieve the aforementioned goal, the performance of complex product assembly tasks should be enhanced. In their work, Kalkan et al. [182] developed a VR training set for assembling a hydraulically controlled clutch complete set with 90 parts in total, and carried out tests on 112 factory workers. The results indicate the reduction of training time by 25%, while improving the assembly task by 27.9%. Furthermore, assembly flaws were significantly reduced by 89%.

Exploiting the advantage of superimposing 3D models onto real scenes, AR has proven to be a great asset in anatomy and the general medical field. Many works investigated and utilized AR for anatomical visualization, including the presentation of 3D lung dynamics in real time, overlayed on a patient in the OR [183]. An important point of consideration is the alignment accuracy of the 3D model on real patients. The work of Fischer et al. [184] discusses the effects of various visualization methods on the ability of users to perceptually align models in breast reconstruction surgeries. Other works involve developing a prototype AR environment for medical training [185], and addressing the problem of having multiple users in the same environment by means of a sharing technique in AR targeted for anatomy training [186].

Specialized medical training is also addressed for glasses-free 3D displays, the benefits of which can be efficiently exploited. Diagnostics, for instance, requires high levels of accuracy which, in turn, is offered by aurostereoscopic devices with accurate depth perceptions. Hence, Kang et al. [62] suggested an eye-tracking-based autostereoscopic system for the navigation of 3D cardiac CT images. Furthermore, autostereoscopic displays can be used in minimally invasive surgery (MIS). Attempts for MIS include the utilization of multi-view autostereoscopic displays for training surgeons by overlaying 3D models of organs onto a real captured video from endoscopic surgery [187], and a 3D interactive surgical visualization system where the medical images conveyed are updated with respect to the observer's viewing direction [188]. Due to their ability to provide a collaborative environment with multiple users, holographic displays can be used in a multitude of defense applications, such as battlespace visualization and fight training [189].

Unlike the case of education, designing LFDs for specialized training may require extremely high spatial and angular resolutions to satisfy the strict requirements related to accuracy. For example, let us consider the case of using LFDs for construction engineering, where exact measures and visualizations are needed from all angles. Hence, designing LFDs for specialized training are extremely expensive, requiring the best the technology has to offer.

Based on the baseline of LFDs, they can be utilized in two ways. For narrow-baseline LFDs, the FOV is small, allowing a single or limited number of viewers simultaneously. Due to the small FOV, this type of LFDs are usually cheaper compared to their wide-baseline counterparts. However, many aspects of LFDs are unaffected by the narrow nature of the baseline (e.g., spatial resolution). Accordingly, this type of LFDs can be utilized in different fields by professionals such as consultants, military personnel, surgeons, and diagnosticians. Regarding wide-baseline LFDs, multiple simultaneous spectators are better supported, and more space is provided for mobility. In our previous works, we considered using this LFD archetype for battlespace visualization [190] and industrial use cases [191]. Generally, regarding the context of military training, we can state that the military may accommodate LF technology well. First, of all, militaries have always been known for their interest in state-of-the-art and experimental technologies. Additionally, if there is one field which has the budget for LF visualization, it is the military. Moreover, as HUD-based solutions are frequent for the control of military vehicles, the best brightness and contrast values are required. For instance, in the context of use cases relying on vehicle-to-everything (V2X) communication, the data visualized on the 3D overlay provided by the LF windshield system must always be clearly perceivable [192]. Furthermore, many different dedicated displays may be relevant to specialized training, particularly the military. For example, in our work on 3D battlespace visualization [190], we characterized a table-like LFD as a multi-purpose (e.g., radar and sonar) station, which in concept is similar to the 3D battlespace solution of Avalon Holographics [193].

Again, various contexts of specialized training—particularly those with greater budgets—do not need the universality of LFDs. In this sense, universality means that a given LFD may accommodate a wide variety of use cases. While it is crucial for elementary and high school education, and may be beneficial for higher education, using an LFD for multiple purposes is definitely not a must for specialized training. One might say that a “one LFD, one purpose” principle may be applicable. By using dedicated display systems, the characteristics of the display may be carefully tailored for the purpose at hand. This is particularly relevant for the FOV; if the LF training station is meant to be used by a single individual, the FOV should consider only the expected movement of the user. Information about the training on the dedicated display may also help adjust the angular resolution—after all, if the expected viewing distance, as well as the complexity and depth of the content are known, then the requirements toward the angular resolution of the LFD can be calculated easily [68]. Therefore, using dedicated LFDs may actually be a more cost-efficient approach than simply relying on high-end universal systems.

In contrast to high-budget contexts, financial considerations may be prohibitive for education and training in low-income regions of the world. Generally, LFDs are exceptionally expensive compared to conventional 2D displays. However, there are multiple ways to circumvent this obstacle. The most cost-efficient method is to visualize an interactive and/or animated LF simulation on conventional 2D displays or on systems that require viewing devices; however, such a solution compromises the very essence of LF visualization. In the scientific literature, 2D displays are often used for the subjective quality assessment of LF contents—particularly due to the unavailability of LFDs. For example, the suitability of 2D displays was investigated by the comparative study of Ahar et al. [194]. Alongside holographic visualization (i.e., a Fourier holographic display), the authors used a laboratory-standard 2D display and a projection-based LFD—namely the HoloVizio 722RC—and found that 2D displays may be appropriate to predict the visual quality perceived on holographic displays. Viola et al. [195] used a similar LCD monitor for interactive (i.e., clicking and dragging with a computer mouse) subjective quality assessment. Relevant examples for glasses-based solutions are the near-eye LFDs of Lanman et al. [196], Jang et al. [197], Zhao et al. [198], and Liu et al. [199]. Alternatively, LFDs may be specifically developed to combat the financial barriers by targeting low yet sufficient KPIs. These may serve in many contexts of general education, yet might not be adequate for specialized training.

7. Conclusions

In this paper, we reviewed the state-of-the-art 3D display technologies in training and education, and addressed the usage of LFDs in different educational contexts, as well as specialized training. While LFDs may be effectively utilized on each and every level of formal education, our analysis indicates that the higher the level of education is, the more strict the KPI-related requirements are. Additionally, higher education and specialized training may greatly benefit from dedicated displays. A takeaway message of this work is that LF visualization technology holds immense potential for future instances of education and training, yet such potential is currently untapped due to the early stages of emergence. However, it should also be emphasized that there is, in fact, a steady increase in the works on LF technology. As LFDs are yet to be introduced to training and education, there is a myriad of research questions that are to be addressed by future works. These include research efforts on perceptual fatigue, as individuals may engage with such display systems for extended periods of time. Research questions on resource-efficient systems are applicable to all forms and levels. This is particularly relevant to lower levels of education, as constraining certain KPIs may not necessarily hinder the effectiveness of the use case. Evidently, the effectiveness and efficiency of such glasses-free 3D visualization should be addressed by comparative performance tests, during which the transfer of skills and knowledge is assessed for various 2D and 3D visualization technologies. Moreover, the interpretation and usage of 3D information in educational contexts should be studied in detail. Numerous series of subjective tests should be conducted in order to investigate perceptual thresholds (e.g., resource-efficiency via perceptual coding), personal preference, immersion, interaction, human–computer interface (HCI), viewing conditions (particularly viewing distance), inter-user effects (especially for larger classes), and many, many more [200].

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Abbreviations

The following abbreviations are used in this manuscript:

3DVT	3D Visual Technology
AI	Artificial Intelligence
AR	Augmented Reality
CNN	Convolutional Neural Network
FATIH	The Action to Increase Opportunity and Improve Technology
FOV	Field Of View
FP	Full Parallax
HCI	Human–Computer Interface
HDR	High Dynamic Range
HMD	Head-Mounted Display
HOP	Horizontal-Only Parallax
HUD	Heads-Up Display
HVS	Human Visual System
I3D	Interactive 3D
IB	Interactive Board
Infitec	Interference Filter Technique
KCL	King's College London
KPI	Key Performance Indicator
LF	Light Field
LFD	Light Field Display
METAL	Mixed Reality Sharing Platform
MIS	Minimally Invasive Surgery
OR	Operation Room
PBL	Problem-Based Learning
QoE	Quality of Experience
ROI	Region Of Interest
S3D	Stereoscopic 3D
SDK	Software Development Kit
SMART	System of Augmented Reality for Teaching
SOP	State Of Polarization
V2X	Vehicle-to-Everything
VAH	Virtual Anatomy and Histology
VOP	Vertical-Only Parallax
VR	Virtual Reality
VVA	Valid Viewing Area
WoS	Web of Science

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