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# A Review on Challenges of Daylight-Based-Classroom-Studies and their Methodology Regarding Architectural-Design-Process

Dherya Mehta

M. Arch, Independent Researcher, Madhya Pradesh, India

**ABSTRACT:** The evolved relationship between humans and nature calls for sustainability with a focus on daylight because various effects of light on humans is known. The importance of education resulted in research studies (considering visual comfort, students' perception, and daylight) and reviews about their methodology. This paper reviews those studies (n=55) to find the challenges they address and the applicability of those methods when it comes to architecture design as a process. The results show that the use of Post-Occupancy-Evaluation (POE) results by one's in practice is critical. The generalizability of outcomes from different classroom studies is questionable, and the researches done in real environments are more reliable than lab studies. The results also mentioned that the present status of simulation software in terms of usability is a severe concern, and there are high expectations from the complicated architecture design process. The suggestions include incorporating the software skills in the undergraduate architecture courses. The use of user-friendly and time-efficient metric/s which aid architects in the initial design stages and the use of a model or software which considers and relates multiple comfort indices is needed. The evaluation of lighting regarding both the daylight and artificial light in real environments is required. Further, the approach to design sustainable buildings must be beyond achieving targeted values, and architects must consider multiple aspects that determine human comfort while designing structures.

**KEYWORDS:** Daylight, Learning environments, Simulation, Architectural design process

## I. INTRODUCTION

The effects of the age-old association of humans with nature may even exist before birth [1]. Many latest survey-based research studies have shown the positive influence of natural environments on humans [2]–[6]. However, due to industrialization and globalization, the direct relation of humans and the natural environment have reduced. In developed nations, people spend maximum time indoors [7] with a change in lifestyle and growing living standards. In the twenty-first century, occupants in office environments spend considerable time indoors [8] and experience more mental labour compared to physical work [9]. This effect is closely related to the other non-residential building occupants as well.

In history, buildings were designed in a way to use daylight efficiently. However, the technological developments enabled the designers to design high-rise and chasmic buildings, which depended entirely on electrical energy for illumination and contained windowless spaces within the core of the interior [10]. On the other hand, the exterior rooms with full height glass windows provided the view and daylight, but on the cost of thermal and visual comfort [11]. A design concept did evolve with a focus on energy efficiency but neglected the importance of excellent daylighting within the buildings. Lately, the depletion of natural resources and technological advancements have driven the concern towards energy efficiency in buildings [12]. A significant part of the present electricity use comes from non-residential buildings because of the frequent use of air conditioning systems and artificial lighting [13]. This energy consumption in buildings depends upon the occupants' comfort criteria, building design, and maintenance [14]. In addition to this, building energy performance is also dependent upon the behaviour of occupants [15]. The energy-saving techniques have reduced a lot of energy consumption in buildings [16], [17]. Lighting consumes a considerable amount of electricity compared to other functions in a building which is associated with many environmental effects, hence using daylight in buildings as a primary light source will reduce the lighting energy demand in buildings [12], [18], [19]. Along with this, reducing the number of artificial lights reduces the cooling load generated from them, which ultimately reduces the total artificial cooling energy requirements [10]. This reduction in the demand for artificial lighting and the depletion of natural resources clubbed with various environmental issues created awareness about sustainability in society.

"One of the basic aims of sustainability is to satisfy the needs of the population without harnessing the perspectives of future generations" [20]. The concern about lighting, in particular, can be addressed by using daylight, which can be incorporated into the building using Passive Solar Techniques (PST). Studies have shown that these PST's were economical [21]–[23]. Many green building rating systems have adopted daylight design strategies [24], the critical aspect being physical metric measurements [25] with not much importance to natural light [21]. In the present scenario, to ensure the effectiveness of energy savings, sustainability must focus beyond the energy-centric approaches and examine occupant comfort, satisfaction, health, and well being [26].

Building design and its characteristics are directly related to occupant comfort [27] and satisfaction [28], which impacts their performance and productivity [29] [30]. The parameters of occupant comfort are temperature, light, sound, indoor air quality, colour, complexity, flexibility, ownership [31], personal control [7], [32], ionization, solar gain, vibrations, safety and security factors, economic concerns [14] and maintenance. However, the exact relationship between these factors is complicated, inter-related [33] and requires more research [27]. At the same time, there are growing demand for improvement in Indoor Environmental Quality (IEQ) factors [34]. IEQ is a good indicator of the performance of a building [35] which includes indoor air quality, acoustics, thermal comfort, and lighting. Poor IEQ harms building occupants [36]. It affects the health and well being [37], [38], performance [36], [38], satisfaction and productivity [37] of the occupants. From all of the factor which may affect the IEQ, visual comfort [39] and lighting [25], [40] are the essential aspects because lighting, primarily through its non-visual medium affects occupant comfort, productivity, and health [41], [42].

Throughout history, daylight has been an integral part of the buildings. Sunlight as a resource is unlimited and freely available, which transforms any space providing the occupants with an emotionally inspiring experience. Hence, this ability to both illuminate an area and to make it more stimulating is one of the main reasons why architects bring natural light into space [43]. Daylight is also a controlled architectural tool [44] that creates lighting effects within buildings, such as focusing at a particular place, highlighting some objects while concealing others, or even totally neglecting its presence in especial cases [11]. Further, it is also the way natural light and building form interacts to give a pleasing experience, along with occupant comfort and energy savings [45]. Illuminating Engineering Society (IES) defines daylighting as who "refers to the art and practice of admitting beam sunlight, diffuse skylight and reflected light from exterior surfaces into a building to contribute to lighting requirements and energy savings through the use of electric lighting controls" [12]. The quality of daylight in buildings can be judged by the quality of visual task performance, occupant satisfaction, its impact on health and well-being, its relation with the perception of space, and its ever-changing nature because of seasonal variations [26]. Daylighting is the design of buildings to use light from the Sun, appropriately done, it supports human health while reducing energy demand [10]. The dynamic nature of daylight is capable of creating our indoor environments with special luminous events [10], for instance, even in an air-conditioned room, people are attracted to sunlight [32], [46]. People have also shown a significant preference for daylight over artificial light, which improved their performance [42]. In brief, the light is essential to humans because it affects them through the visual, psychological, biological, and physiological systems [47], [48].

## II. BACKGROUND - "CLASSROOMS, STUDENTS AND VISUAL COMFORT"

Education has always been of prime importance in human society. It exercises both the mental and physical state of a person to provide a set of knowledge, skills, and abilities [49]. Education and employment are directly related to the overall development of a nation. In the present scenario, due to technological advancements and lifestyle changes, students spend maximum time within their classrooms [31], [36]. The relationship between education, employment, and technology decides a person's value in society [50]. However, urbanization and industrialization affected the evolution of classroom designs [51]. In the present scenario, many different activities that require specific visual settings happens in the same classroom [52]. The activities include reading, writing, and communication [49] supported by audio and visual tools, computers, and internet access [53]. All these regularly developing advancements have made learning more interactive, at the same time, an additional issue for the designers [54]. There is a constant challenge of increasing the number of students per classroom [55]. All of these factors affect classroom design. Students have also shown a preference for personal control in the classrooms [32]. Overall classroom climate has small-to-medium positive associations with social competence, motivation and engagement, and academic achievement [56].

To evaluate the effect of classroom design on occupants, students' perception of their classroom is unavoidable. Student's perceptions about their classroom environment include psychological, psycho-social, and physical environment (ambient environment, spatial environment, and technology) [53]. Out of all these attributes, lighting is



close to the pupil's learning [39] and their behaviour [57]. Good lighting in classrooms ensures student's performance, motivation, alertness, attention [29], and concentration [58]. Artificial lighting causes visual (strain) and non-visual (fatigue and circadian dysfunction) effects among students [59]. A classroom's overall lighting is important for ensuring better circadian entrainment because the effect of the circadian system is more on children than on adults [60]. In this overall lighting, daylight plays a very significant role. Classrooms devoid of daylight may upset the hormone pattern of children, which may affect their concentration, annual body growth, and sick leave [61]. Daylight in classrooms have shown positive effects on students' health, well-being, performance [19], [22], [59], [62], behavior, productivity [63], and even seating preference [32], [63] of the students.

Daylight in the present scenario due to the vertical development of buildings, most of the time, especially in learning environments, is admitted through windows. Windows have a complex effect on occupants [19]; still, people prefer them for daylighting working environments [64]. Windows connect occupants to the ever-changing views of nature [65]. Scenes of nature, the external world, and contact with outdoor spaces have shown positive effects [11], [55]. Outside views increase mood and productivity [10], [12], and provide information about weather, time of day, and surrounding activities [10]. A recent study assessed the effect of a window on the emotional and thermal response on 86 participants in a lab setting. It found that having a window enhances psychological well-being by improving positive emotion and reducing negative emotions, and providing a visual connection to the outdoors supports working-memory and concentration that may be directly related to a worker's productivity [66]. Hence daylight through/and windows affect visual comfort within classrooms.

Visual comfort in classrooms is also directly related to energy consumption because of the use of artificial lights. An insufficient quantity of daylight may increase energy consumption because of the use of artificial lights, on the other hand, extra natural light, with unequal distribution may cause glare and excessive solar gain [67]. Hence, if the fair use of daylight reduces the need for artificial lights, it can be an essential strategy for energy efficiency in the buildings. Further, the benefits from sunlight are hard to reproduce through artificial light, which has several adverse effects [59]. Nevertheless, imagining a workplace that relies only on natural light is not possible. Hence, daylight and its interaction with artificial light are essential [68].

Several metrics, ways of measurements, and methods have been developed over the years to access the lighting quality and quantity. The required amount of light ensures good quality but is not the only determinant [69]. An integrated approach must examine the lighting quality. The latest study proposed a Lighting Quality Assessment Method (LQAM) to assess lighting quality in educational rooms using the analytic hierarchy process using lighting criteria and sub-criteria with related evaluation indicators. These are amount of light, glare, colour appearance, flexibility and healthiness, which have a different impact on overall lighting quality [70]. Further, the environmental setting, type of activities, aesthetics, various human needs (safety and security) [69], and their characteristics [71] will also decide the appropriateness of good lighting.

The evaluation of daylight spaces needs accurate methods beyond building regulation, design techniques, which also includes performance in terms of human comfort [43]. A subjective and objective evaluation of the thermal, acoustic, and lighting comfort conditions in university classrooms concluded that the combination of measurements and questionnaires provides a complete overview of classroom environmental quality [72]. Subjective measures to assess lighting quality are general evaluations of lighting quality, questions examining discomfort glare, indoor environmental quality scales, and affective response scales [40]. The objective measurements of the lighting quality include direct and indirect measurements. Direct measurements are the once which use only one single metric to describe overall lighting quality, whereas, the indirect measures use multiple metrics to describe lighting quality [73]. The most common metric for assessing daylight exploitation are Illuminance, Uniformity ratio, and Daylight factor [11]. However, time-varying predictions (climate-based metrics) proved to be more realistic than these metrics [43]. These include Useful Daylight Illuminance (UDI), Daylight Autonomy (DA), Spatial Daylight Autonomy (sDA), Annual Sunlight Exposure (ASE), Discomfort Glare Probability (DGP), and Spatial Visual Discomfort (SVD) [11]. High Dynamic Range (HDR) imaging technology has also been proved helpful [74]. Many daylight simulation tools to analyze the daylighting performance of a model in various environmental settings, such as Radiance, DAYSIM, Energy Plus, and Dialux [75] are useful. These simulation tools avoid the costly and time-consuming field data collections [76].

### III. THE NEED FOR THE STUDY

The importance of buildings and education in human society along with the benefits of daylight calls for the investigation of similar researches. Many kinds of research in learning environments (schools, classrooms, lecture halls, university rooms, libraries) regarding students' comfort, preferences, indoor lighting, and visual comfort using questionnaire forms, onsite measurements, and simulations are going on. These studies have contributed a lot towards improving the quality of classrooms, but with their respective limitations. These limitations basically can be categorized into two segments, first being the challenges in the methodology adopted for conducting them and second the difficulty in the adoption of results by the professionals in practice for the overall improvement of educational spaces. Hence, there is a need to perceive these barriers with the intent of improving the future designs of learning environments.

### IV. AIM AND METHODOLOGY

The paper addresses the classroom related researches and reviews intending to find the limitations mentioned by various authors. The article also highlights the importance and challenges of the architecture design process addressed by these researches.

A set of keywords (lighting, educational, daylight, classrooms, visual, comfort, satisfaction, Indoor Environmental Quality, light in architecture) were searched based on the domain of research. The identified papers were then sorted based on abstract and detail reading. Post detailed reading of those selected papers, certain specific terms were found which served as a keyword to be searched. Table 1 summarizes the different combinations of the keywords. The past 11 years review papers and the past three years research papers were found. The type and number of documents referred are shown in Table 2. The articles are classified as Classroom-Based Studies (CBS) and Non-Classroom Based Studies (NCBS), which are further divided into Research Papers (RSP) and Review Papers (RvP) respectively, along with the year of publication.

S.No.	KEYWORD
01	(humans) AND (nature OR natural environment)
02	(humans OR occupant) AND (buildings) - energy
03	(nature) AND (buildings) - energy
04	(indoor environmental quality) AND (buildings) - energy
05	(buildings) AND (daylight OR natural light)
06	(health) AND (daylight)
07	(health) AND (buildings)
08	(classroom design OR lecture halls OR learning environments) AND (student behaviour)
09	(windows) AND (visual comfort)
10	(measurements) AND (lighting quality) AND (visual comfort) AND (school OR classroom OR lecture halls OR learning environments OR educational spaces)
11	architectural design

Table 1. List of Keywords Searched.

### V. RESULTS

Many types of research in various classroom environments have used questionnaire surveys as an important tool. An investigation of classrooms in Greece to find the side effects of natural light using Post Occupancy Evaluation (POE) stated that POE studies are a useful tool to study indoor daylight conditions [77]. A study on school building design considering environmental comfort stated that POE's should be a part of the school design process to avoid repetition of errors [78]. Most of the POE study uses scales. A work analyzing the affective response of 918 students (from 30 different universities) to their classrooms mentioned that this approach has a limitation as the scales used in the survey may not be interpreted by the interviewees correctly [79]. On the other hand, a recent study evaluating the accuracy of daylight metrics in architectural studios concluded that the existing knowledge about the questionnaire and survey process does increase the accuracy of results [80]. Similarly, the latest research on lecture halls of higher education institutes relates survey results (n=207) to daylight simulations. One of the results of this study showed that the architects were able to predict the daylight simulation results better than non-architects [81]. However, it would be incorrect to expect the awareness level among participants regarding the respective surveys. The research examined the

effect of lighting conditions on 181 students from three different studies. Their concern was the studies to evaluate lighting effect on achievement and behaviour of school students vary concerning the research design, types of lighting systems, target groups, and outcome measures [58].

A study analyzed a total of 854 students' affective responses to their luminous environment in 29 classrooms. They stated that conducting these type of studies in real environments is a difficult task; on the other hand, studies based in laboratory environments generally uses easily manipulative electrical lighting [54]. A work evaluated the effects of artificial light's colour temperature on 16 students in a controlled setting and found that relying on a single index for evaluating lighting of classrooms in controlled lab experiments in insufficient [82]. A review of 58 field and laboratory studies, which included a significant number of studies on educational environments. It showed that either the disturbance caused to participants during data collection in field studies or the preconceived notions of the participants in the lab experiments might affect the participant's perception of glare [83]. There is a concern about the poor agreement between laboratory-derived measures and the experience of occupants in real spaces by a survey and simulation-based study in a studio space occupied by 500 students [84].

S.No.	YEAR	NUMBER OF STUDIES REFERRED			
		CBS		NCBS	
		RsP	RvP	RsP	RvP
01	2020	4	1	4	3
02	2019	3	NA	3	2
03	2018	4	NA	NA	1
04	2017	5	1	NA	1
05	2016	3	NA	2	2
06	2015	4	NA	5	2
07	2014	2	NA	1	1
08	2013	6	1	1	2
09	2012	2	1	1	1
10	2011	4	NA	3	2
11	2010	2	NA	NA	1
12	2009	1	NA	NA	1
13	2008	2	NA	1	NA
14	2007	1	NA	1	NA
15	2005	NA	NA	1	NA
16	2004	1	NA	NA	1
17	2003	NA	1	NA	1
18	2002	2	NA	NA	NA
19	2000	1	NA	NA	NA
20	1992-98	1	NA	NA	1

Table 2 Types and Number of Papers Referred.

A research work evaluated the classroom's visual performance adopting a simulation-based approach in which a wide range of combinations between viewers' points and centres of interest within a classroom restricted to evaluate only the extreme and critical locations [85]. Most of the parameters used in lighting design consider the threshold or average values [86]. However, a study which evaluated the luminous comfort in a drawing classroom using HDR pictures stated that the use of average values is not the ideal way to analyze environments with specific illumination needs [13]. A simulation-based approach to evaluate the visual comfort of 5 architecture classrooms mentions the software and simulation process becomes time-consuming whenever we rely on accurate data [87]. A simulation-based approach adopted to assess the daylighting performance of a classroom stated that single criteria are not sufficient to analyze a space [88]. An evaluation of daylight in a research institute building using simulations addressed the fact that multiple

simulation prototypes of buildings are a very labour-intensive process and provide only a few design interventions [89]. Most visual comfort research today focuses on the comfort of an individual at a single instant [84]. A holistic measurement, simulation, and survey-based approach to evaluate visual comfort in natural lit classrooms stated that dynamic metrics along with the upper and lower values, do not assure visual comfort and visual discomfort [90]. The effect of the light may be the situation, task, and time-dependent [58]. It is possible to experience some instantaneous visual discomfort and still find a space agreeable overall [84].

The challenges regarding visual comfort in classrooms are not limited just to the technical aspects. A review that discusses previous researches on how to bridge architecture with other domains to address daylighting design stated that the ever-changing nature of sunlight forces architects to rely on intuition and experience to evaluate this dynamic nature of sunlight [26]. A research study suggested a daylighting design method by combining a passive approach and advanced software to design external shading devices for daylighting in a classroom. It mentioned that the amount of time that the simulation software consumes to evaluate and analyze the design, the expert knowledge which they require, the large amount of data input, and the difficulty to apply them on the initial design stage hinder their use by the architects [21]. Architects are using digital tools during the design process. These tools target a range of set values. However, due to the wide range of parameters that contribute to the good daylighting design [26], the targeted values may not reflect the actual scenario. The engineering-oriented attitude furthers the distance between engineers and designers without coming to a common conclusion [21]. The architects face these highly variable multiple aspects which conflict but need to be brought together for the final satisfying solution [26]. For example, consideration of thermal and daylight analysis in the initial design stages could be helpful to provide indoor comfort along with achieving energy efficiency buildings. Still, high thermal mass does provide thermal comfort but on the cost of reduction of daylight within the interiors [91]. A simulation-based method study to access daylighting in a housing prototype mentioned that the architects' affection for natural light lies in the fact that it can transform a space [43]. Architects understand the benefits of natural light in terms of enhancing visual interest, providing emotional and experiential delight to the observers [26]. A POE based study of the visual environment in a laboratory building told that Architects should wisely incorporate daylight into buildings to ensure the right amount, intensity, distribution, and penetration at the same time avoiding glare [18]. A review study focusing on the effects of indoor lighting on students' performance concluded that lighting quality must consider the combination of daylight and artificial light [29]. A review evaluating the design and implementation of various daylighting systems mentioned that solutions to lighting design are no longer universally versatile [12]. The individual diversity of comfort preferences contributes to the uniqueness of the design [26]. However, the aim of a design process is not to come up with an optimal solution instead to produce a range of satisfactory ones with different priorities and compromises [92]. Even when one comes up with an optimal solution, there are no criteria that can test a given solution nor a process in which such criteria could be applied [26]. A school building design based study considering environmental comfort stated that the design of a building is a complex process that involves professionals and technicians from various fields [78]. A daylighting impact analysis on the performance of students in school mentioned that the engineers, educational theorists, and construction economists did not come on the common ground regarding classroom design [19]. However, a study done on various design processes involved in the design of passive Danish homes concluded that there is a need of all the professionals involved in the building design to work together from the very beginning of the design process [93]. In general, the architects' role concerning the expectations is forever evolving [94]. The research outlining the results of 14 case studies where architects and their clients used few techniques to evaluate their buildings or design process at any stage in the life cycle of a project mentions interesting fact. It stated that the designers in practice rather than analyzing the behavior of the completed building and subsequently using the outcomes, jump to another project which may lead to the repetition of errors [95]. The financial affordability of the POE studies along with the lack of interest among architects is also an issue [96]. The "grass root globalization" which may be adopted by acting locally (by incorporating traditional architecture) and globally (using technical advancements) is the need of the hour but an another additional challenge to the architects in the modern world [97].

## VI. DISCUSSION

The findings from the classroom studies and architectural design process focus on five different concerns. First is the POE studies and surveys. POE studies are useful for documenting occupant's well-being and responses to indoor environmental factors [25]; they aid in building design, efficiency, management, and use of the building [9]. Still, the analysis from the POEs and their availability for the one's in practice is a question [31]. The second concern is about the generalizability of results from various researches done in different learning environments and different climatic zones. Thirdly the difference in real classroom studies and the controlled lab experiments. The controlled experiments in lab settings create a gap between research and practice [25]. Fourth being the use of metrics and simulations because they are time-consuming, require a high amount of expertise, and aim at target values. In addition to this, a significant

number of simulation tools are difficult to learn [75], and the available metrics are difficult to calculate during the design stage [98]. The fifth is the forever evolving architectural design process itself which is a very complicated task involving case-specific highly variable multiple aspects; to meet at one final solution.

The latest developments in the metrics and simulation software for predicting daylight and the overall lighting within any learning environment stresses on its use at the early design stages. Nevertheless, the question is of the knowledge and expertise the present architects have about them. This concern highlights the suggestion of incorporating the software and skills in the undergraduate architecture courses. There is a need for user-friendly and time-efficient metric/s which aid architects in the initial design stages. The use of a model or software which considers and relates multiple comfort indices, especially thermal and visual comfort, at the same time is essential. Further, the evaluation of energy-efficient interior lighting must consider both daylight and artificial light in real environments. The architects' approach to design sustainable buildings must be beyond the aim of achieving minimum average targeted values. The architects, along with other professionals involved in building design, must come to a conclusion that must consider the present environmental scenario but not on the cost of multiple aspects that determine human comfort.

The limitation of the research is that it covers only the learning environments; on the other side, similar results are incomplete unless tested on other buildings (especially office) types as well.

## VII. CONCLUSION

The affected relationship between humans and the natural environments throughout history calls for sustainability. Many green building rating systems have come up with the design strategies, but mostly focusing on the physical metric measurements. The limitation here is that even when light affects humans through the visual, psychological, biological, and physiological system is known, these green building rating systems have not considered natural light of much importance. Building design and its characteristics are directly related to occupant comfort. Various studies have been done, which highlights the importance of natural light and windows in learning environments. However, this importance is worth only when daylight interacts with artificial light. Interior lighting quality out of all the IEQ factors is significant. Nevertheless, students' perception of their classroom and the physical attributes which can affect their productivity is a long list. The ways to access lighting quality include POEs and direct and indirect measurements based on static and dynamic metrics. All these methods and metrics come with limitations. The limitations will become more challenging if architects find it difficult to use these metrics on the initial design stages.

The findings from the study state that

- the use of POE results by the one in practice is critical,
- the generalizability of results from different classroom studies is questionable,
- the researches done in real environments are more reliable than the lab's experiments,
- the present status of simulation software in terms of usability is a serious concern, and
- there are high expectations from the complicated architecture design process.

Suggestions include

- incorporating the software and skills regarding DPM's in the undergraduate architecture courses,
- use of user-friendly and time-efficient metric/s which aid architects in the initial design stages,
- the use of a model or software which considers and relates multiple comfort indices,
- the evaluation of lighting regarding both the daylight and artificial light,
- researches in real environments,
- the approach to design sustainable buildings must be beyond achieving targeted values, and
- architects must consider multiple aspects that determine human comfort while designing structures.

The research analyzes various classroom related studies only, which is a limitation because the similar results are incomplete unless evaluated on other buildings (which consider daylight within interiors) as well.

## ABBREVIATIONS

(PST), Passive Solar Techniques; (IEQ), Indoor Environmental Quality; (IES), Illuminating Engineering Society; (LQAM), Lighting Quality Assessment Method; (UDI), Useful Daylight Illuminance; (DA), Daylight Autonomy; (sDA), Spatial Daylight Autonomy; (ASE), Annual Sunlight Exposure; (DGP), Discomfort Glare Probability; (SVD),



Spatial Visual Discomfort; (HDR), High Dynamic Range; (POE), Post Occupancy Evaluation; (DPM), Daylight Prediction Methods; (CBS), Classroom Based Studies; (NCBS), Non-Classroom Based Studies; (RsP), Research Papers; (RvP), Review Papers.

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