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Using Classroom Lighting and Acoustical Systems to Enhance the Diverse Visual and Auditory Sensory Needs of Children with Autism

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Abstract

If students with disabilities are not accommodated in learning environments, then they are unlikely to learn important skills and may struggle to live independently within society [1]. Sensitivities to visual and auditory stimuli have been found to result in distraction, discomfort, unwanted behaviors, and poor learning outcomes for students with autism. This systematic literature review includes recommendations for lighting and acoustics that were identified as important considerations for integration within K-12 educational settings. Recommendations are organized into four areas: two are Lighting (electric and daylight sources) and two are Acoustics (air-based and assembly-based transmission). These recommendations led to the development of a general set of classroom design guidelines to support the needs of children with autism.

Keywords: Autism, Classroom, Built environment, Acoustics, Lighting.

Introduction

Individuals with autism, or Autism Spectrum Disorder (ASD) may experience hyper- (high) or hypo- (low) sensitivity of the senses in varying degrees, especially to sound, light, touch, taste, smell, pain and other stimuli [2-4]. Many people with ASD live with auditory hypersensitivity (hyperacusis) and are overly sensitive to loud noises, appear to hear noises before others, and cannot function well with background noise. Caldwell and Mostafa indicate that acoustics are the most important factor of the environment influencing the behavior of children with autism [4-6]. People who are hypersensitive to visual stimuli are often bothered by bright lights, easily distracted by movement, stare at certain people or objects, and prefer soft muted colors whereas those who are hyposensitive to visual stimuli often disregard people or objects in the environment, can see only outlines of certain objects, and often like bright colors and bright sunlight [5]. Clearly, people with autism vary widely in their responses, abilities, and behaviors and may experience symptoms that include difficulty understanding what others are thinking and feeling; social communication challenges; restricted repetitive behaviors, interests, and activities; and cognitive delays, which can make designing for these disparate needs difficult [1].

ASD, the ADA, and building codes in educational environments

Across the U.S., many schools have assessed and modified their special education curriculum/programs to support the increasing numbers of children with ASD. As specialists continue learning more about people with ASD, an area still requiring attention is the impact of the built environment within these educational settings to support their ability to learn and enhance overall quality of life [7]. While visibility of individuals with ASD within society is increasing, many designers and architects still know little about the diverse needs of this group. The literature suggests that the built environment can serve as a support or deterrent to children with ASD, and that there is an increased likelihood of creating supportive environments when designers and architects are sensitive to sensory issues. Although the design and architectural communities have effectively integrated building codes and the Americans with Disabilities Act (ADA) Standards into their design solutions since the early 1990's, many of these codes and standards address physical needs while overlooking "hidden" needs (e.g., developmental, and sensory processing issues), in part due to their lack of knowledge [1]. Although people with autism have the same desire for functional, accessible spaces that the rest of society enjoys, research shows that there is often a problematic relationship between individuals with autism and their surrounding environment.

When possible, U.S. federal law requires children with disabilities, including people with ASD, to be educated in a general education classroom. Specifically, the Individuals with Disabilities Education Act (IDEA) "guaranteed access to a free appropriate public education (FAPE) in the least restrictive environment (LRE) to every child with a disability" [8]. Although this is not optimal, for all students on the spectrum, for many, learning within an inclusive environment with other neurotypically developing students has benefits [9]. Regardless of a school district's philosophy, there is clearly an underlying belief that students with ASD need to learn somewhere, and it is the authors' belief that the classroom environment is critical to the learning process and should be designed to cultivate autonomy and positive learning experiences for all. For some students with autism, the unfortunate reality is that many existing classroom environments are designed in such a way that their ability to learn the skills needed to become successful and included members of society is hindered [10]. Modifying the classroom design for these students has been shown to enhance learning, reduce negative behaviors, and increase attention span. Although students with autism are impacted differently by the environment than typically developing students, the fact remains that a well-designed classroom can serve as an important teaching tool for enhancing learning, or negatively affect education through poorly planned spaces [1,11].

Since people with ASD have a wide range of sensitivities, including visual, auditory, vestibular, olfactory, and proprioceptive or tactile, recommendations often appear to contrast with one another. This again highlights the importance of developing and implementing flexible solutions that increase autonomy. The built environment is multifaceted and consists of many layers, but two components related to building systems that can benefit or hinder learning by students with ASD are lighting and acoustics. When considered intentionally, lighting and acoustical systems can help to minimize sensory distractions for students who are hypersensitive and facilitate sensory integration for students who are hyposensitive. Having previously identified a small body of work on visual and acoustic classroom interventions in the built environment, the authors decided to undertake a scoping review to identify new or previously unknown research and best practices. These two bodies of research were combined to provide guidance and direction for new areas of research.

Materials and Methods

In September 2021, the authors searched the following databases: PubMed, CINAHL Plus with Full Text (EBSCO), PsycINFO (ProQuest), ERIC (ProQuest), Web of Science, and Scopus Table 1. There were no date limits applied. Three hundred and fifty-eight studies (358) were exported from the databases into Rayyan (https://rayyan.ai) for screening, and 130 duplicates were removed as seen in Table 2. As above, the authors had previously identified 35 works of research that were core to this area and included in this review. Some of these studies are not peer-reviewed journal articles but help to inform the best practices identified in the peer-reviewed literature. Two authors screened the 263 unique results, with a third author serving as tie-breaker. Two hundred and four articles were excluded during abstract screening according to the inclusion and exclusion criteria displayed in Table 2. The 59 remaining studies were screened in full text, and an additional 13 were removed for not matching the inclusion criteria. This left 46 studies used in this analysis, as seen in Tables 3-6, and are noted with an asterisk in References. See Figure 1 for the screening process.

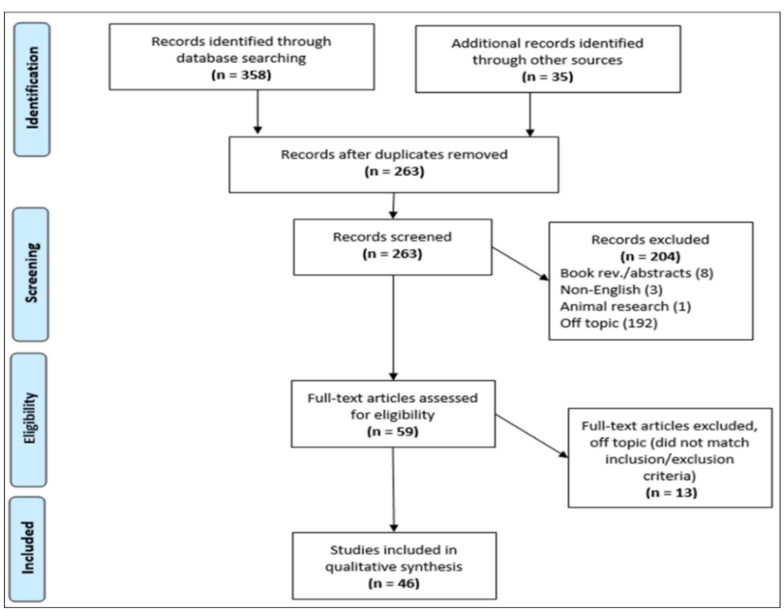

Figure 1: Searching process using the PRISMA 2009 flow diagram.

Topics	Keywords	MeSH (PubMed)	Subject Headings (CINAHL)
School Environment	school; students; teachers; classroom	Schools; Students; School Teachers	Schools+; Teachers; Students+
Built Environment	interior design; built environment; classroom environment; built classroom; classroom design; classroom space; built pedagogy; learning space; learning environment; school space; school environment; educational space; educational environment	Interior Design and Furnishings; Built Environment; Environment Design	Interior Design and Furnishings+; Built Environment; Learning Environment+
Autism/ASD	autism; autistic; ASD	Autistic Disorder; Autism Spectrum Disorder	Autistic Disorder
Sensory	proprioceptive; proprioception; hypersensitivity; hyposensitivity; sensory; perception; hearing; acoustics; acoustical; sound; auditory; vision; visual; seeing; sight; lighting; illumination; illuminance; glare; flicker; fluorescent; LED; reverberation; signal noise ratio; sound transmission class	Proprioception; Perception; Feedback, Sensory; Sensory Gating; Hearing; Acoustics; Speech Acoustics; Sound; Auditory Perception; Speech Perception; Pitch Perception; Timbre Perception; Loudness Perception; Vision, Ocular; Visual Perception; Lighting	Proprioception+; Perception+; Sensory Defensiveness; Hypersensitivity+; Hearing+; Acoustics+; Speech Acoustics+; Sound+; Auditory Perception+; Speech Perception; Voice Perception; Pitch Perception; Loudness Perception; Vision+; Visual Perception+; Lighting

Table 1: Search Terms.

Inclusion Criteria	Exclusion Criteria
English language journal articles	Book reviews, abstracts
Visual/lighting impacts of the built classroom on children with autism	Non-English articles
Auditory/acoustic impacts of the built classroom on children with autism	Animal/non-human research
	Articles focusing on those with ADHD or other learning disabilities
	Articles focusing on adults with autism
	Articles on social aspects of autism (e.g., inclusion; bullying)
	Articles on children with autism who are also deaf, blind, hearing or vision-impaired
	Articles focusing on teaching/learning/curricular interventions and not the built environment
	Articles focusing on visuals not tied to the built environment (e.g., room displays; visual activity schedules)
	Articles focusing on developing or validating assessments of the built environment

Table 2: Inclusion and Exclusion Criteria.

Results

Individuals with ASD experience an altered perception of sensory stimuli and processing of information within environments [12]. Shabha and Gaines and Shell indicate that some environmental factors including background noise, glare, visual clutter, and the presence of large numbers of students and teachers create negative stimuli [13,14]. Sounds of other children, outside noises, and the echo of sounds within rooms were identified as three environmental noises that resulted in children avoiding classroom activities and lashing out in aggressive behaviors to those around them [15].

Pillar and Pfeiffer shared that appropriate modifications to acoustics and lighting within the built environment increased the attention of children within school environments while Gaines et al. indicated that limited or well-controlled sensory stimuli helps students learn and remain focused [9,16]. In some cases, these approaches showed a tripling of enhanced attention span, 60% decrease in response time, and a 60% decrease in instances of self-stimulatory behavior [6]. Below the literature findings regarding lighting and acoustics is communicated.

Sensory Information Related to Vision and Lighting

Visual stimuli from light have a significant impact on students' learning success in the classroom. Fernandez-Andres et al. emphasized the importance of limiting visual input, such as uncontrolled light within classrooms, to minimize distractions to other students [3]. As we discovered in our review, adequate, and well-controlled light is necessary to provide opportunities for learners to see visual cues such as body language and facial expressions, to aid in assessing situations around them (e.g., Mostafa, 2014b) [17]. Therefore, a careful balance must be attained between light quality that is distracting and light quantity that is required to perform specific visual tasks effectively and safely (i.e., reading and writing without eyestrain; or navigating through space without tripping). Tables 3 and 4 include design characteristics that can promote desired outcomes related to visual sensory information and lighting in the built environment.

Light quality typically includes lighting characteristics exclusive of measurable illumination levels for specific visual tasks and activities [18]. There is an inherent interrelationship between light phenomena as part of the electromagnetic spectrum of energy, the color correlations of specific wavelengths of visible light, and human color vision. Therefore, light quality includes color as a characteristic. Correlated color temperature (CCT) is the appearance of the color of light emitted by a light source as warm, neutral, or cool. Color rendition (CRI) is the degree of color shift due to the interaction of light wavelengths on pigmented objects [18]. Gaines et al. reported that bright colors and intense light can be distracting or bothersome depending on whether the individual is hyposensitive or hypersensitive [19].

Grandgeorge & Masataka hypothesized that children with ASD who are hypersensitive to visual stimuli may show an aversion to the color yellow due to its high luminance value and potential for visual fatigue [20]. Pence, et al. addressed the use of blue light covers over fluorescent light fixtures to mitigate sensory distraction; however, the results showed that sensory distraction increased [21]. Overall, this review of the literature did not indicate a preponderance of research focused specifically on the effects of light and color on children with ASD.

One primary cause of sensory disruption related to light quality in classrooms is glare. Glare may result from daylight or electric sources, and includes direct glare (e.g., visibility of excessive light directly at the source) and indirect glare (e.g., visibility of excessive light reflecting off a smooth surface). While glare can be differentiated as discomfort or disability glare, it is a common unintended result of light that negatively impacts vision and visual tasks [18].

Therefore, light diffusing textures need to be factored into lighting solutions for classrooms as much as the light sources themselves. Indirect lighting (i.e., light that is directed upward to reflect off ceiling planes, mitigates direct glare and provides diffuse light while also hiding that actual light source. While glare impacts all people, children with ASD are less likely to be able to regulate their responses [22,23].

Another major cause of sensory disturbance in children with ASD is related to fluorescent and discharge electric light sources due to the physics of how they emit light. Sensitivity to fluorescent light is associated with magnetic ballasts and flicker. Simply put, these types of fluorescent fixtures flicker due to hertz (Hz) modulation from the ballast that drives the electric current and produces light. The light output from these fluorescent fixtures pulse, and the frequency or rate at which it is measured, is referred to as Hz modulation.

Sensitivity to modulation can be visibly distracting at lower ranges (i.e., below 100 Hz) because the eye constantly tries to adapt to changing light levels resulting in increased susceptibility to eye strain, headaches, and reduced visual performance. Modulation of 100 Hz is problematic because modulation (flicker), while not visible, is still perceived by the brain which results in a subconscious experience where headaches, distraction, and poor task performance can occur. Numerous studies identified increased sensitivity to Hz modulation by children with ASD. Electronic ballast fluorescent fixtures are less likely to cause modulation at lower Hz modulation. Anecdotal reports indicate that mitigating glare and Hz modulation by covering fluorescent fixtures with colored lenses or filters may be effective for students with ASD, however these strategies have not been confirmed to be effective [21].

Multiple studies indicate that including daylight sources (i.e., properly placed windows and skylights that mitigate glare and heat gain) improve academic performance overall, both for students with ASD and those who are typically developing [12,17,19,22-27]. The qualities of daylight or full-spectrum natural light ensure excellent color rendition, high illuminance levels without disability glare, overall impressions of brightness, and contributions to biophilic response (e.g., connections to nature, and circadian rhythm enhancement).

Furthermore, studies indicate that student performance improves in classrooms that include full-spectrum daylight. Table 4 includes a full list of design characteristics that promote desired outcomes related to visual sensory information and daylighting in the built environment.

Design Recommendations	Sources
Utilize LED lighting and minimize dependence on fluorescent fixtures due to modulation/flicker and associated headaches, reduced visual performance, interruption of circadian rhythm, and impact on individuals with auditory or visual hypersensitivity.	Fenton & Penney, 1985; Gaines et al., 2016; Mallory & Keehn, 2021; C. Martin, 2016; R. Martin & Wilkins, 2021; Paron-Wildes, 2005; Sánchez et al., 2011; Shell, 2019; Tola et al., 2021; Treichel 1974; Winterbottom & Wilkins, 2009.
If specifying fluorescent fixtures include high color rendition lamps to avoid color shift and metameric failure that may cause distraction.	Gaines, Curry, Shroyen, et al., 2014.
Avoid distraction and sensory triggers such as glare, especially those associated with fluorescent sources which may result in repetitive behaviors.	Gaines, Curry, Shroyen, et al., 2014; Martin, 2016; Shabha & Gaines, 2013; Shell, 2019; Wexler & Luethi-Garrecht, 2015.
Utilize carpet or small rugs in place of or over vinyl or linoleum flooring to diffuse light and eliminate distraction due to glare.	R. Martin & Wilkins, 2021; Winterbottom & Wilkins, 2009.
Use residential looking commercial light fixtures for task lighting. Select light fixtures that minimize the feeling of being in an institution, and sources that may be hidden from sight to reduce glare, thus achieving indirect and diffuse illumination	Paron-Wildes, 2005; Vogel, 2008.
Specify full spectrum lamps, (e.g., incandescent, halogen, and LED), to mimic natural daylight and ambient color and reduce disruptive behavior, limit flicker and excessive brightness associated with fluorescent lamps.	Kinnealey et al., 2012; Lyons, 2002; Shapiro et al., 2001; Tola et al., 2021; Woodcock et al., 2009.
If specifying fluorescent fixtures include high color rendition lamps to avoid color shift and metameric failure that may cause distraction.	Gaines, Curry, Shroyen, et al., 2014.
Use high frequency electronic ballasts instead of low frequency magnetic ballasts, or frequency control circuitry on fluorescent fixtures to reduce modulation (flicker) to reduce headaches and eye strain, improve task performance, increase accuracy in reading, and improve visual search performance.	Gaines, Curry, Shroyen, et al., 2014; Knez, 2014; Paron-Wildes, 2005; Vogel, 2008; Winterbottom & Wilkins, 2009
Calculate illuminance levels using all sources (daylight and artificial) that fall within recommended guidelines of 300 lux to 500 lux (i.e., approximately 30 footcandles to 50 footcandles), and position fixtures to provide uniform illumination levels across student desks.	Winterbottom & Wilkins, 2009.
Locate controls for electric light sources such as switches and dimmers, conveniently for teachers.	
Minimize reflected glare and visible sheen on vertically mounted whiteboard surfaces and minimize the use of dry-erase whiteboards (DWBs). When DWBs are used, they should be mounted so that the base is slightly tilted away from the wall surface to reduce glare.	
Utilize interactive whiteboards (IWBs) due to their diffuse reflection of light and lowered visible sheen.	Winterbottom & Wilkins, 2009.

Provide flexibility through light switches that control room lighting to a smaller bank of light fixtures, or to every other fixture, to reduce lighting in pre-selected areas of the room.	Gaines et al., 2014; Martin, 2016; Warman, 2019; Winterbottom & Wilkins, 2009.
Recognize the correlation between the use of fluorescent lighting and a greater frequency of stereotypical behavior (e.g., arm flapping, banging, tapping, body bouncing and rocking, body whirling and twirling, foot tapping, and hand clapping, etc.).	Fenton & Penney, 1985.
Specify blue-enriched, high CCT LED light sources, as they can increase attention and cognitive processing.	Mallory & Keehn, 2021.
Recognize the effectiveness of using colored lenses or filters over fluorescent lights to mitigate modulation and glare (the effectiveness of this has not been verified. For example, modified lighting (i.e., addition of blue-light covers to fluorescent light fixtures) has not been found to increase on-task behaviors in children with ASD).	Gaines, et al., 2014; Pence et al, 2019.
Include additional lighting over student work areas to increase visibility but be cautious of increasing shine or glare on work surfaces.	Wexler et al., 2015.
Integrate other light sources (e.g., LED, and incandescent) to alleviate some brightness throughout the day, if fluorescent light sources are the only light source.	Gaines et al., 2014.
Use one or two banks of fluorescent lights; if there is more than one bank of lights use separate switches.	Gaines, et al., 2014.
Include lighting with varied and changeable color to suggest wayfinding.	Uherek-Bradecka, 2020.
Specify dimmers, along with switches, to allow for adjustable brightness and light intensity.	Tola et al., 2021; Uherek-Bradecka, 2020; Warman, 2019.

Table 3: Visual Sensory Information and Associated Building Systems: Electrical Light Sources.

Design Recommendations	Sources
Use and integrate daylight sources that provide diffuse illumination, (e.g., north facing windows with sills above eye-level and skylights) to reduce reliance on artificial sources and to minimize glare, and exterior visual distractions.	Denhardt, 2017; Gaines et al., et al., 2014; Mallory & Keehn, 2021; Martin, 2016; Martin & Wilkins, 2021; Mostafa, 2014b; Tola et al., 2021; Wexler & Luethi-Garrecht, 2015; Winterbottom & Wilkins, 2009; Woolner et al., 2007.
Minimize the depth of spaces, from window walls in classrooms to allow deeper daylight penetration with continuous daylight glazing (e.g., clerestory windows located high on exterior walls).	Khattab & Al-Mohaisen, 2005; Tola et al., 2021.
Utilize interior glazing in walls separating corridors from classrooms for improved daylight penetration without glare, when skylights are located in corridors.	Khattab & Al-Mohaisen, 2005.
Orient windows along north and south facing walls to optimize daylight.	Khattab & Al-Mohaisen, 2005.
Use windows that provide flexibility (e.g., opened, closed, raised, or lowered), to control heat gain and excessive daylight. Measured illuminance levels may be more than twice that which is desirable.	Al-Mohaisen, 2006; Gaines et al., 2016; Tufvesson & Tufvesson, 2009.

Utilize continuous windows on north and south facades to achieve uniform daylight penetration, and avoid daylight illumination that creates dazzling sun entrances, glare, deep shadows or excessive contrasts, patterned or rhythmic shadow-light sequences, silhouetting, etc., which may produce visual overstimulation and unwanted distraction.	Al-Mohaisen, 2006; Mostafa, 2014b; Tufvesson & Tufvesson, 2009.
Utilize lightshelves with smooth surfaces and high light reflectance values to improve the penetration of daylight into the classroom. Interior lightshelves should be located on windows with northern orientations and slightly sloped downward for greater efficacy.	Al-Mohaisen, 2006; Khattab & Al-Mohaisen, 2005.
Utilize white louvers within double pane glass on south facing windows to provide flexibility and control of excessive daylight while limiting glare and heat gain.	Khattab & Al-Mohaisen, 2005.
Use smooth, white ceiling surfaces for classrooms to maximize daylight reflection toward the floor.	
Use sandblasted or similarly treated glass, skylights or clerestory windows to generate a diffuse and homogeneous illumination from natural light.	Gaines et al., 2014.
Avoid excessive daylight illuminance levels and control excessive daylight illumination through operable window coverings (e.g., blinds and shades) that allow teachers to alter lighting levels.	Jebril & Chen, 2021; Martin, 2016; Tufvesson & Tufvesson, 2009; Winterbottom & Wilkins, 2009.
Avoid the use of horizontal, venetian blinds as window coverings to eliminate patterns resulting in glare discomfort.	Winterbottom & Wilkins, 2009.
Locate controls for daylight sources, such as blinds, conveniently for teachers.	
Remove displays from windows to allow more natural light to enter the classroom, reducing the need for electric lighting.	Martin et al, 2019.
Avoid locating classroom windows near highly reflective exterior surfaces (e.g., parked cars and windshields, glazing and some cladding materials) to avoid reflected glare into classrooms.	McAllister & Hardjiri, 2013.
Utilize dimming daylight sensors to gradually dim electric light sources as the target illuminance of 500 lux or the equivalent of 46.5 footcandles on desk surfaces is attained.	Khattab & Al-Mohaisen, 2005.
Plant trees in strategic places outdoors to filter daylight and provide diffuse lighting for interior spaces.	Tola et al., 2021.

Table 4: Visual Sensory Information and Associated Building Systems: Daylight Sources.

Sensory information related to sound and acoustics

Sound or noise is the result of sound wave vibrations transmitting through a medium. In buildings, sound transmission typically falls into two categories: airborne (i.e., sound moving through air and small openings or gaps between spaces), and structure-borne (i.e., sound resulting from physical impact and vibrations on and through building surfaces). Sound is also categorized according to the location of the source. Internal sources include sounds from inside the building (e.g., mechanical equipment as well as human activity), while external sources include sounds from nearby transportation systems, construction activities and environmental events (e.g., seismic activities, and wind, etc.).

The problems associated with poor acoustics (e.g., inability to hear faint sound levels, discomfort caused by high noise levels, distraction by background noise and echo, etc.), exist for everyone in a classroom environment. However, children with ASD are particularly susceptible to sound-based distraction, and other sensory difficulties with Kanakri identifying sounds from air conditioners, children in the classroom and other classrooms, and echoes as some of the main sources of noise that negatively impacted behavior [28]. The more accurately that students with ASD can process auditory information, the easier it is for them to comprehend and respond to their environment both socially and academically. For the purpose of this review, sensory information related to acoustic criteria has been categorized as airborne sound and structure borne sound, although the two are related with one type impacting and potentially contributing to the other (i.e., mechanical system sound vibrations becoming airborne).

Sound can be controlled through a variety of acoustic approaches, including the use of sound absorbing materials, sound masking systems, and the elimination of objects that inherently produce unwanted sound. Factors contributing to sound and acoustics include reverberation, signal to noise ratios, and background noise, all of which impact hearing and sensory processes. Both reverberation and background noise impact the subjective impressions of pitch, (i.e., very low sound levels such as a hoarse voice, and very high sound levels such as a whistle), and loudness, (i.e., intensity of sound from the low end of the hearing threshold to the high end of the hearing threshold causing pain) and are of equal value in determining acoustic control in classrooms.

Mostafa identified acoustics as the most critical sensory element to consider in the environment related to autistic behavior when planning [6,17,29]. In fact, empirical research has shown that reducing noise levels and echo in educational spaces for children with ASD has positively affected their attention spans, response times, and behavioral temperament as measured by instances of self-stimulatory behavior [17]. However, Bogdashina reiterated the need to remember that other students may be hyposensitive to noise and may seek sound to stimulate their hearing by banging doors, tapping items, and tearing or crumpling paper [30]. Mostafa recommended that the level of acoustic control should be integrated according to the level of focus needed for the activity occurring within a space, as well as the skill level and severity of autism [17]. For example, an activity requiring higher focus should include a higher level of acoustical control to minimize background noise, echo, and reverberation. Tables 5 and 6 include a list of design characteristics originating from the literature review findings that promote desired outcomes related to auditory sensory information and acoustics in the built environment.

Design Recommendations	**Sources**
Encourage the use of acoustical materials that consider the different properties of finish and construction materials (e.g., sound-absorbing panels installed over drywall or suspended from the ceiling, and carpet instead of vinyl composite tile) in high focus areas to assist in removing distracting acoustical sources.	Gaines et al., 2016; Kanakri et al., 2017a; Kinnealey et al., 2012; Mallory & Keehn, 2021; Manlove et al., 2001; Pillar & Pfeiffer, 2016; Sánchez, 2008; Tola et al., 2021.
Minimize background noise and other excessive noises, but do not fully soundproof rooms, to allow students to acclimate to and become used to spaces with a variety of noises.	Mostafa, 2018.

Minimize distraction and sensory triggers caused by excessive noise.	Mostafa, 2018; Shabha & Gaines, 2013; Shell, 2019.
Specify sloped ceilings that gradually decrease in height moving toward the back of classrooms so that sound carries away from teachers without causing echo. Ceiling reflectors also help sound to travel to the back of the classroom from the front.	Gaines et al., 2016; Jebril & Chen, 2021.
Stagger doorway spacing to eliminate direct routes for sound transmission.	
Maintain ceiling heights from 9’-0” to 12’-0” for optimal acoustical conditions in classroom spaces. Lower ceiling heights increase noise levels as the result of sound reflectance and closer proximity of students with ASD to HVAC fans and equipment.	Bradley, 1986; Jebril & Chen, 2021; Tola et al., 2021.
Consider the maintenance and cleanability needs of material selections. Soft materials, such as carpet, can be useful in absorbing noise but are harder to clean than hard surfaces.	Martin, 2016.
Consider the use of soft-music or subtle pink noise in classrooms to provide sensory stimulation and to block classroom noises to benefit students with ASD during some activities but take care to screen children for hearing impairments.	Gaines, 2014; Jebril & Chen, 2021; Pillar & Pfeiffer, 2016; Sánchez et al., 2011.
Use biophilic background noises (i.e., a water fountain wall, in outdoor courtyards) to mask background noise and help relax and focus the minds of students who are hearing impaired and/or auditory hypo-sensitive or hyper-sensitive.	Clark, 2003; Sánchez et al., 2011.
Avoid hard surfaces on ceilings, walls, and windows.	Clark, 2003; Mostafa, 2014b; Tola et al., 2021; Vogel, 2008.
Use suspended acoustic ceiling tiles (ACT), and acoustic wall panels to reduce reverberation and echo as compared to a harder ceiling surface such as gypsum.	Clark, 2003; Manlove et al., 2001; C. Martin, 2016; Tola et al., 2021.
Alleviate reverberation/echo through room configuration, sound absorbing materials, and limit reverberation to 0.4 seconds to assist individuals who are autistic to distinguish between foreground and background noises.	Gaines et al., 2016; Kinnaer et al, 2016; Manlove et al., 2001.
Ensure that SNRs in occupied classrooms exceed +15 DbA (teacher to background) to guarantee that children fully understand speech from teachers.	Kanakri et al., 2017b; Manlove et al., 2001; Mostafa, 2014b; Pillar & Pfeiffer, 2016.
Reduce the distance between the teacher and children to increase SNR and lower reverberation.	
Recognize that higher SNRs may result in increased speech levels by teachers, resulting in vocal fatigue, strain, and limited verbal exchanges.	
Recognize that children need higher SNRs than adults.	
Use sound absorbing materials (e.g., upholstered furniture, acoustic wall panels, cork boards, “wall quilts” and carpeted floors) to reduce reverberation, help “diffuse the echo” and eliminate excess stimuli.	
Recognize that children who have difficulty understanding speech, particularly in noisy settings, often develop habits of not paying attention to speech. This results in fewer opportunities of engagement which can impact their learning and development.	
Provide acoustic baffles to limit noise transfer.	Denhardt, 2017.
Eliminate unnecessary background noise sources, such as music playing in the background, ticking clocks, computers, televisions to increase student focus and have fewer outbursts.	Gaines, Bergen, Curry & Shin, 2014; Kanakri et al., 2017b; Manlove et al., 2001; Sánchez et al., 2011; Tufvesson & Tufvesson, 2009.

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Remember that very young children have increased instances of chronic hearing problems from infections or fluid build-up but may not exhibit outward signs of being ill, such as fever.	Manlove et al., 2001.
Incorporate hard surface walls behind the teacher to help transmit vocal commands toward students.	Clark, 2003
Control or mitigate exterior noise transmitted by nearby traffic, outdoor equipment, playgrounds, and sport facilities.	McAllister & Hardjiri, 2013; Mostafa, 2014b; Tola et al., 2021; Wang & Brill, 2021.
Insulate exterior walls to decrease reverberation time of external noise.	Mostafa 2014b, 2015.
Use sound-field amplification systems (SFA) to amplify educators' voices above ambient noise.	Mallory & Keehn, 2021.
Cluster high stimulus functions in similar sensory zones and separate noisy areas from quiet areas.	Mallory & Keehn, 2021; Mostafa, 2014b.
Specify suspended ceilings, fiberglass and acoustic ceiling tiles, padded carpet, and wall panels to limit reverberation.	Gaines & Sancibrian, 2014.

Table 5: Auditory Sensory Information and Associated Building Systems: Airborne Sound.

Design Recommendations	Sources
Incorporate wall assemblies consisting of two layers of drywall over staggered studs with sound-absorbing insulation within the stud cavity, and staggered drywall seams.	Gaines et al., 2016; Sánchez et al., 2011.
Locate fluorescent light fixture ballasts high in the ceiling to control sound.	Paron-Wildes, 2005.
Avoid the use of fluorescent light fixtures to reduce buzzing and humming associated with them.	Kinnealey et al., 2012; Martin, 2016; Mostafa, 2015; Tola et al., 2021.
Repair or replace malfunctioning fluorescent light fixtures that create background noise.	Manlove et al., 2001.
Provide a minimum Sound Transmission Class (STC) rating of 50 for wall assemblies with full-height construction from the floor to the underside of the slab above, with acoustical insulation within stud cavities and double layer gypsum board surfaces on each side of the studs to mitigate airborne noise transmission.	Clark, 2003; Gaines et al., 2016.
Locate air-handling units further away from areas that may be sensitive to noise (e.g., in-room air conditioners/HVAC units and roof mounted air handlers directly above classroom spaces.	
Use in-floor heating instead of ceiling and wall vents to reduce extra auditory stimuli within the classroom.	
Limit exterior noise transmission through windows with isolated or specialty laminated assemblies.	
Provide Impact Insulation Class (IIC) rating of 45 for floors, which can be achieved by using soft flooring materials such as carpet or suspended acoustical ceiling tiles (ACT) in the ceilings of spaces above and below to diminish the impact-based noise	
Avoid large openings in walls and partitions above the finished ceiling for HVAC ducts, and incorporate acoustic linings and silencers, or heavier gauge ductwork to insulate mechanical noise.	Clark, 2003; Gaines et al., 2016.

Provide thermal insulation in wall and ceiling assemblies to avoid reliance on fans and air conditioning units that create noise.	Jebril & Chen, 2021.
Design HVAC ductwork to lead from inside a classroom to the corridor to minimize sound transference to adjacent spaces.	Gaines et al., 2016.
Maintain recommended SNR of 15 dB, although there are indications that SNRs exceeding 20dB are recommended for children with hearing or learning impairments.	Wang and Brill, 2021.
Design the acoustics within a classroom to reduce external noise permeation as well as internal echoes through use of high-quality wall systems/construction.	Mostafa, 2014b; Mostafa, 2015; Mostafa, 2008; Tola et al., 2021.
Design a group of rooms with diverse levels of soundproofing so that children can graduate from one level of acoustical control to another to acquire the necessary skills to scaffold to a non-controlled environment.	
Specify six-inch-thick walls and high-density vinyl barriers to minimize sound transfer between spaces.	Gaines & Sancibrian, 2014; Tola et al., 2021.
Specify green roofs to reduce noise from rain.	Tola et al., 2021.
Install quieter fans and other HVAC equipment.	
Reduce number and size of wall and ceiling openings in rooms requiring high acoustical quality (speech therapy, quiet rooms).	
Provide manual switches for fans to avoid sudden loud or startling activation of equipment.	
Specify double or triple-glazed windows and heavy curtains to increase sound absorption and reduce outdoor sound transmission.	

Table 6: Auditory Sensory Information and Associated Building Systems: Impact and Structure Borne.

Discussion

While much research focuses on how children with autism can learn to develop strategies for coping with sensory input from the built environment, the authors believe that it is possible to favorably influence the behavior of children with autism through intentional planning of stimulus inputs from lighting and acoustics, even with their diversity of needs. Previous work by Mostafa, as well as her studies included in this review have shown that this proactive approach has enhanced behavior and created environments that promote skill development, especially in the area of acoustics design [6,15,31]. Within classroom environments, it is important to capitalize on every learning opportunity, including understanding and manipulating sensory input from the surrounding environment [17].

It is important to understand the impact of the environment when designing classroom spaces for children with ASD and to highlight elements that impact children' visual and auditory sensory perceptions, such as lighting and building systems. It is equally important to consider the exposure of students with ASD to ideal environments (i.e., well-controlled and planned spaces for neurodivergent users) while preparing them to experience non-ideal environments. Learning environments should help prepare children with ASD to develop the abilities to effectively function in environments designed for use by neurotypical individuals. This review has taken a research-based approach to developing a list of autism-friendly design guidelines for use in K-12 classrooms, with the potential for positively impacting the design of the classroom environment.

When focusing on visual sensory information, there is consensus on the importance of full spectrum lamp specifications to mimic the quality of natural daylight. It is equally important to integrate quality daylighting whenever possible. Daylight strategies must be used with care to avoid glare and excessive illumination with attention to planning and implementation. While the use of blinds and shades may be used to control daylight, true daylighting strategies should be integrated architecturally and with electric lighting systems. Avoiding fluorescent light fixtures due to noise and modulation is recommended, although many children are likely to be educated in classrooms that have fluorescent lighting, since it is often a building standard within older commercial facilities. Therefore, in these situations, the recommendation is to use high frequency electronic ballasts instead of low frequency magnetic ballasts, or frequency control circuitry on fluorescent fixtures to reduce modulation (flicker) which, will reduce headaches and eye strain, improve task performance, increase accuracy in reading, and improve visual search performance. Although the use of LED lighting is recommended due to its superior energy efficiency and lack of ballasts resulting in modulation, it is important to consider the impact of fluorescent lighting technology in schools in general. Given the prevalence of mainstreaming students with ASD with their neurotypical peers because of the Individuals with Disabilities Education Improvement Act of 2004, and the costs associated with replacing entire lighting systems, there is an increased likelihood that students with ASD will learn within buildings having fluorescent lighting systems, although in an ideal setting these would be eliminated. Therefore, the recommendation for fluorescent sources remains viable.

Sensitivity to acoustics was identified by Mostafa as the number one priority when designing for children with ASD [17,20]. Incorporating elements that absorb sound and reduce excess interior and exterior noise (e.g., acoustic ceiling panels, wall/floor treatments, and dedicated playground spaces) for children who are hypersensitive is key. However, there are additional recommendations related to the physics of sound and its movement through air or structures in buildings. Careful planning of HVAC systems and their locations, the configuration of spaces, the construction of wall and ceiling assemblies must be balanced by the achievement of optimal Signal to Noise Ratio (SNR) and reduced reverberation levels which require technical assessment.

What is most difficult in this work is the fact that responses to stimuli are varied depending on the hyper- or hyposensitivity needs of each child. For example, recommendations by Pillar & Pfeiffer indicated that calming music could be used to block classroom noises to benefit hyposensitive learners [16], whereas Kanakri et al., Manlove et al., Sánchez et al., and Tufvesson & Tufvession recommended the elimination of unnecessary background noise sources such as music playing in the background, ticking clocks, computers, and televisions to minimize distractions and sensory triggers for hypersensitive learners [32-35]. In short, providing flexibility by providing adaptable design solutions, especially with users having a wide range of sensitivities, is important.

Additionally, contradictory recommendations based on system type indicate that strategies for improved daylighting may cause acoustical problems or vice versa. To increase daylight penetration into spaces, smooth light-colored surfaces are recommended for ceilings and walls. However, Clark, Mostafa, Tola et al., and Vogel, recommend acoustical ceiling tiles which have lower reflectance values and are less effective for daylight penetration yet improve the control of sound within classrooms [12,17,36-40]. Therefore, acoustical control and daylight integration may be at cross purposes. This highlights part of the problem that has existed in creating effective spaces for students with autism and the need for flexibility in the development of solutions. A common phrase repeated frequently in the world of autism is, "If you know one person with autism, you know one person with autism," and that continues to be emphasized in the recommendations by researchers that are often at cross-purposes to one another. Finally, the authors caution against taking Band-Aid or low-budget approaches without clear knowledge or understanding of highly technical lighting and acoustical systems and the objective to be met within the space [21].

While reviewing the selected publications, the authors noted several areas of research needing further expansion. This review of literature does not indicate a preponderance of available research focused specifically on the effects of light and color on children with ASD. For example, children respond differently to color and clarifying whether soft colors are soothing to both children with ASD who are hypo- and hypersensitive would be effective to increase understanding of behavior and performance. If children who are hyposensitive to color desire more stimulation than what is offered by soft, pastel colors, then research could look at how flexible methods of providing color within a space could meet the needs of both (i.e., a soft background color with brighter colors on a drapery system that could be pulled into place as needed to increase stimulation). Knowledge of other aspects of the built environment (e.g., textiles, textures, and furniture, etc.) in classrooms and the effects they have on children with ASD would be beneficial.

Conclusion

Auditory and visual sensitivities are the most frequently cited sensory distractions for students with autism, indicating the need for focused collaborative research between the disciplines. The authors believe that this type of approach would lead to effective research-based solutions in classroom design and can extend beyond lighting and acoustics for a more comprehensive understanding of learning environments. The results of this scoping review indicate that there is an intersection between the recommendations by researchers in the areas of lighting and acoustical design and the research of those who are focused on sensory issues related to autism. Creating interdisciplinary research teams that consist of designers, architects, technicians, school administrators, special education teachers, and parents will provide collaborative resources that address a wide range of solutions benefitting students with ASD, and likely all users.

Conflict of interest

There is no conflict of interest.

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