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A review exploring convergence insufficiency in younger populations and e-devices in the digital era

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Background: The advancement of the fourth industrial revolution has increased the penetrance of e-devices among younger populations, particularly with e-learning technology which has become widespread due to special circumstances such as the coronavirus disease 2019 (COVID-19) pandemic.

Aim: The purpose of this review is to explore the prevalence of convergence insufficiency (CI) in younger populations and to map any associations between CI, near work and e-device usage.

Method: A comprehensive literature search was conducted using Elsevier, PubMed, Medline and Ebscohost databases. The literature search used the following keywords in various combinations: 'Convergence Insufficiency', 'Binocular vision status of primary school children', 'E-learning', 'M-learning', 'Computer vision syndrome', 'Digital eye syndrome', 'E-devices and children'.

Results: The observed prevalence of CI ranges from 5.46% to 13.00% among non-clinical studies and from 3.50% to 18.00% among clinical studies. The prevalence among primary school children ranges from 6.80% to 31.40% whilst CI among high school children may be as prevalent as 32.60%, depending on the diagnostic criteria employed. There is mixed evidence showing the association between screen time and myopia. No studies were identified showing a direct association between CI and e-device use.

Conclusion: Convergence insufficiency has proven to be a prevalent condition among both young children and young adult populations. There is a need for studies to investigate the prevalence of CI in younger populations who learn in a digital environment. This may highlight exposure to the modifiable factor of screen time in managing the condition in the context of a tech-infused lifestyle.

Keywords: convergence insufficiency; binocular vision disorders; e-learning; digital eye strain; computer vision syndrome; primary school children.

The issue

Convergence insufficiency (CI) and vergence anomalies are becoming increasingly prevalent in our society and may impact younger populations. With the advancement of the fourth industrial revolution (4IR), more intensive near visual requirements are required of young children.[1] The coronavirus disease 2019 (COVID-19) pandemic has exacerbated this, resulting in schools adopting online learning methodologies. The resultant increased near work and increased exposure to electronic (e) devices is concerning, as, despite no single causative factor being identified, factors such as intensive near work increase the likelihood of developing CI.[2]

Studies often described near work activities as the time spent reading books or writing using pen and paper. However, in our current digital environment, one must account for the presence of digital devices or electronic (e) devices when describing near work. Thus, contemporary definitions of near work have expanded to include e-device usage.[3] Younger users have readily embraced e-devices as an almost integral component of their daily lifestyle. Studies have shown that children as young as two years old spend up to 2 hours a day using e-devices, pre-COVID-19.[4,5]

Contrary to popular belief, reading on a screen or electronic device does not have the same effect on the visual system as reading off a printed document.[6] The characters on a screen are not always displayed at optimal contrast and the presence of glare and reflections from the screen result in visual strain and fatigue. In addition, characters on a screen are comprised of pixels, bright central dots with ill-defined edges that may cause eye strain.[7] The presence of blue light emitted from

light-emitting diode (LED) screens also contributes to visual fatigue.[8,9] The visual symptoms associated with e-device use have proven similar regardless of whether the user is interacting with a laptop computer or a mobile smart device.[9,10,11,12] The presence of asthenopia and other visual and ocular symptomology due to e-device usage is known historically as computer vision syndrome (CVS). More recently, CVS is referred to as digital eye syndrome (DES) to extend the definition to include other digital devices.[13,14,15]

Digital eye syndrome is a universal term that has become common as it encompasses the visual effects induced by all digital devices, including desktop computers, smart phones, laptop computers and hand-held tablet devices. Digital eye syndrome is commonly experienced by adults; however, there is some evidence of children developing symptoms of DES, including dry eye, blurred vision and headaches.[13,16] Unlike adults, children may not be able to accurately communicate any symptoms that they experience, hence it is possible for DES to remain undiagnosed in young children.[17] Studies[11,18,19,20,21,22,23] conducted on young children collectively agree that prolonged e-device use has a negative impact on ocular health.

Convergence insufficiency is one of the most documented and prevalent vergence disorders.[24] Recognising whether an association exists between the use of e-devices, which constitutes near work, and CI will compliment DES concerns. E-devices such as hand-held devices are usually held closer than printed material which places added strain on the vergence system.[25] Young children may be especially vulnerable to this as their visual systems are still developing. The purpose of this review is to assess the evidence that exists regarding CI in young children and investigate whether an association can be found between CI and e-device usage.

The condition – Convergence insufficiency

Convergence insufficiency is an anomaly of binocular vision characterised by difficulty performing near tasks. Patients present with symptoms including headaches and diplopia associated with near work, blurred near vision, asthenopia and loss of concentration when reading or performing close work. Other, less common symptoms include nausea, dizziness, grittiness of the eyes and general fatigue. The clinical manifestation of CI includes a receded near point of convergence (NPC), a near exophoria (XOP) that is greater than the distance XOP by 4 PD (Prism dioptres) or more, reduced positive fusional vergence (PFV) (Base out reserves) and reduced negative relative accommodation (NRA).[1]

The clinical presentation of all four of the aforementioned signs in patients with CI is relatively uncommon, as such, sub-classifications of CI exist as shown in Figure 1. *Classic* CI is diagnosed when three of the above-mentioned clinical
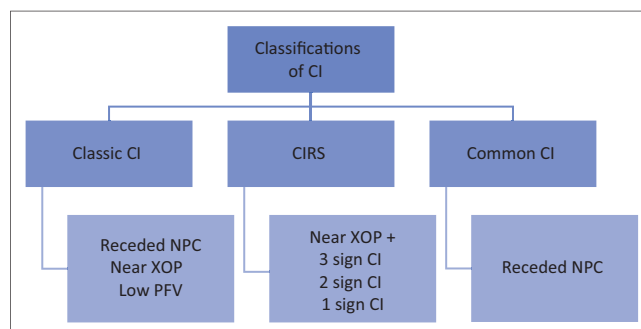
CI, convergence insufficiency; CIRS, Convergence Insufficiency Reading Study; XOP, exophoria; PFV, positive fusional vergence; NPC, near point of convergence.

FIGURE 1: Classifications of convergence insufficiency. Signs include near exophoria greater than the distance phoria by 4 prism dioptres, receded near point of convergence, reduced positive fusional vergence.

signs are present viz, a receded NPC, a near XOP that is greater than the one at distance by 4 PD or more and reduced PFV.[26] *Common* CI is diagnosed using only a receded NPC.[15] Another approach based on the Convergence Insufficiency Reading Study (CIRS)[26] involves grading the severity of the condition according to the number of signs present. Patients may present with a near XOP and any of the following: three other signs of CI, two other signs of CI, one other sign of CI or they may be classified as non-exophoric with no CI. The other signs of CI include the near XOP being greater than the distance phoria by 4 PD, low PFV and a receded NPC.[27]

The problem

Convergence insufficiency is the most prevalent binocular vision disorder;[28,29] however, it shows a highly variable clinical prevalence. The observed prevalence ranges from 1.75% to 25.00% in adults.[1,30] Possible reasons for this variance could include studies using different clinical definitions (Figure 1), differences in the populations being studied (clinical setting vs population-based) and the techniques and instrumentation used to obtain measurements.[1,30] Traditionally, CI has been observed in adolescents and young adults. At these ages, symptoms include asthenopia and visual fatigue as sufferers simultaneously become involved with more intensive near work. The assumption was made that young children do not experience enough near work for it to have an effect on their vergence systems.[31]

Advancements in modern technology have led to more intense near visual requirements placed on children at younger ages. Contributing factors to this may include urbanisation and the associated lifestyle; that is, the presence of computers and other e-devices, the large extent to which they are utilised and higher educational attainment. Pandemics such as COVID-19 that warrant social distancing also contribute to an increased near demand through increased usage of e-devices for work or study.[4] The effects of the above-mentioned factors may be starting to present themselves as a study found that 13% of children in grades five and six presented with CI, with almost 80% of those diagnosed presenting with an associated accommodative insufficiency.[32]

The changing educational approach for learners: E-learning

E-learning is a rapidly growing aspect of traditional learning that encompasses various technologies, forms and components. It is considered to be the third learning system in the history of human learning, using electronic techniques and smart devices, or e-devices, as a primary medium of learning.[33] No single definition of E-learning exists, each definition focusses on a unique aspect of E-learning methodology.[34]

Abbad et al.[35] broadly defined E-learning as any type of learning that is electronically enabled. This encompasses learning that is web-based or internet-based and applied in settings such as online distance learning, hybrid learning or distributed learning. Web-based learning is widely considered to be a breakthrough in the field of E-learning, with universities and higher education facilities embracing the concept for correspondence students. Algahtani[36] subdivided E-learning as being either computer-based or internet-based and cites the rapid development of personal computer technology, such as laptop computers, smart devices and wireless networks, as being integral to this kind of E-learning model. Computer-based learning makes use of software programs that assist in the learning process, known as E-learning applications. In contrast, internet-based learning makes use of online courses and information available on the internet.

Another aspect of E-learning that is becoming more prevalent in modern society is that of M-learning (Mobile learning). M-learning expands on the concept of E-learning highlighted by Algahtani,[36] involving the use of hand-held mobile devices such as tablets and smart phones to supplement traditional classroom learning. M-learning users are able to download various types of software that assist in the learning process. In this aspect, M-learning has a definite advantage over traditional E-learning in that the mobile devices are portable and cheaper than traditional desktop computers, which are often bulky and fixed in one place. Thus, students are able to access both online teaching platforms and educational software from any location at their convenience. In addition, using a form of technology that students are comfortable with contributes to this model of E-learning gaining more popularity with users.[37]

The educational sector represents the largest area of E-learning. Higher education institutions commonly make use of online learning portals to provide additional classroom information and encourage mobile device usage to access these portals.[37] At a schooling level, E-learning is integrated into the system by two means, *versus* technology for learning and technology for learners. Learning technology is designed to be an educator tool that is used to supplement traditional classroom teaching. Learner technology refers to applications designed to engage the student and makes use of media that the student is likely already comfortable with, including social media and gaming applications. There has been debate as to the effectiveness of learner technology, and learning technology has become increasingly common in recent years.[38] E-learning has become increasingly commonplace in recent times, as the COVID-19 pandemic forced primary, secondary and tertiary education institutions to adopt E-learning methodology as the primary teaching method during the global lockdown.

The increased penetration of E-learning into schooling systems raises concern around the visual health of the learners. Replacing traditional reading and writing material with e-devices increases the risk of school children developing DES and other visual problems. Lifestyle changes that have been put into place during the COVID-19 further exasperate the problem. With many employers opting to work from home, school and higher education facilities have followed suit and have replaced traditional classroom teaching time with online learning. This resultant increased exposure time to digital devices (or increased screen time) consequently increases the risk of developing DES. Since electronic devices are used at a near working distance, convergence and accommodation are most at play. If CI is already a prevalent vergence issue, the question remains as to whether exposure to e-devices will result in a new generation of young e-device users presenting with an increased prevalence of CI.

Literature search

A comprehensive literature search was conducted within the period of August 2018 to March 2021. Databases including Elsevier, PubMed, Medline and EBSCOhost were used to source evidence through the reference manager application Mendeley. The literature search used the following keywords in various combinations: CI, Vergence Anomalies, Binocular vision status of primary school children, CI and children, E-learning, CVS, DES, E-devices and children, Vision and near work, CI and digital devices. After title screening and abstract screening, data were extracted from full text articles that satisfied the selection criteria. All relevant English language publications were included and organised by category, that is, CI, E-learning or E-devices and CVS related and then by year.

Convergence insufficiency in the clinical versus non-clinical population

The reported prevalence of CI is 25.0% in a clinical setting and 7% in a general population setting.[31,39] More recent reports show that the prevalence ranges from 3.5%[40] to 17.6%[26] among clinical populations and among non-clinical populations, the prevalence may vary from 5.46%[41] to 13%.[42] However, these values are influenced by the study population. Clinical populations comprise individuals presenting to hospitals or clinics. Non-clinical studies may be conducted at any location and participants are enrolled from the general population. The prevalence of CI will be discussed in terms of clinical and non-clinical populations as shown in Table 1.

TABLE 1: Convergence insufficiency in the clinical versus non-clinical population.

Study	Year	Population (*n*)	Age (years)	Criteria for diagnosing CI	Prevalence (%)
Non-clinical					
Richman et al.[42]	2002	University students (48)	24–31	Two or more classic clinical signs present: • A near XOP greater than the phoria at distance • Receded NPC • Reduced positive fusional reserves • Low NRA	13.0
Sharif et al.[43]	2014	University students (160)	18–30	Three classic clinical signs present: • NPC greater than 10 cm • Near XOP greater than the distance XOP by 4 PD or more • Low convergence amplitude	10.0
Hashemi et al.[41]	2017	General (2219)	10–69	Four clinical signs present: • NPC equal to or greater than 6 cm • Near XOP greater than the distance XOP by 4 PD or more • Low positive fusional reserves • Normal accommodative amplitudes as per Hofstetter's formula	5.46
Clinical					
Lara et al.[40]	2001	Clinic (265)	10–35	Five clinical signs: • Moderate to large near XOP • Low positive fusional reserves • Receded NPC and *two* of the following: • Low NRA, Low MEM, Low AC/A ratio or failing binocular accommodative facility with +2.00 DS (less than 3 cpm)	3.5
Rao[45]	2014	Clinic (182)	8–49	Three clinical signs: • Receded NPC • Reduced positive fusional reserves • Low NRA	18.0
Ming-Leung et al.[46]	2019	Clinic (415)	21–38	Three clinical signs: • Near XOP greater than the one at distance by 4 PD or more • Receded NPC break (greater than 6 cm) • Low positive fusional reserves/Fails Sheard's criterion	9.6

CI, convergence insufficiency; XOP, exophoria; NPC, near point of convergence; NRA, negative relative accommodation; PD, prism dioptres; cpm, cycles per minute; MEM, monocular estimation method retinoscopy; AC/A, accommodative amplitude to accommodation; DS, dioptre sphere.

Non-clinical population

Richman et al.[42] investigated the prevalence of binocular and accommodative disorders in a population of United States-based optometry students aged between 24 and 31 years old. The study found a 42% presentation of some form of binocular dysfunction among the population. Convergence insufficiency was the second most prevalent disorder with a prevalence of 13%. A similar study conducted by Sharif et al.[43] investigated the prevalence of CI among Iranian university students and found that 10% of those tested presented with CI.

More recently, a lower prevalence of CI was observed by Hashemi et al.[41] The study reported a prevalence of 5.46% CI in an Iranian sample. The study also noted emmetropes and hyperopes were slightly more likely to develop CI, although no statistically significant correlation was found.

The studies by Richman et al.[42] and Sharif et al.[43] employed similar age ranges, with the study conducted by Richman et al.[42] including some older participants whilst Sharif et al.[43] included slightly younger participants (Table 1). Both studies recognised the high prevalence of CI when compared to that of a general population. Sharif et al.[43] suggested that this may be linked to the intensive near demand experienced by students. Richman et al.[42] found symptoms worsened with any form of near work, thus reinforcing the causation of near work inducing strain on the vergence system. Despite differences in the respective diagnostic criteria, the above studies have noted a significant prevalence of CI among university students. Considering the population, the high prevalence is likely to be due to the excessive amount of time that university students spend studying and on other near tasks. This warrants the need for further studies including children and considering both CI and near work to be conducted, including any association with e-devices, given that e-devices are used at a near working distance.

The studies (Table 1) appear to indicate an overall decrease in the incidence of CI. However, it must be noted that both the more recent studies employed methodologies with increasingly stringent diagnostic criteria which does result in a lower prevalence, as noted by Nunes et al.[44] Furthermore, the broad age range employed by Hashemi et al.[41] may have resulted in a lower observed prevalence.

Clinical population

Lara et al.[40] investigated the prevalence of accommodative and vergence disorders in a clinical population between the ages of 10 and 35 years old. The prevalence of CI was found to be 3.5% among this population. The authors employed a five clinical sign diagnostic criteria, including a near XOP that is greater than the distance XOP by 6 PD, reduced positive fusional reserves and a receded NPC.[2] Another clinic-based study conducted more than a decade later by Rao[45] sought to determine the prevalence of non-strabismic disorders among asthenopic patients. Hospital-based patients between 8 and 49 years old showed an 18% prevalence of CI. The authors employed a less stringent diagnostic criteria to diagnose CI when compared to Lara et al.[40] (three clinical signs to diagnose CI). This may account for the higher observed prevalence, as liberal diagnostic criteria have been noted to result in a higher observed prevalence of CI. However, given that the study was conducted at a time when e-device usage was extremely commonplace, the possible visual effects of the sustained near focus required of e-devices may also be a contributing factor.

Ming-Leung et al.[46] investigated the prevalence of binocular dysfunctions among Chinese adults and investigated associations with refractive error. Convergence insufficiency was found to be the second most common disorder in this population, with a reported prevalence of 9.6%. The study employed three sign diagnostic criteria to diagnose CI and noted that emmetropes were more likely to present with CI, in agreement with Hashemi et al.[41]

Two of the above-mentioned studies that included younger participants were shown (Table 1). The study conducted in 2001 by Lara et al.[40] reported a much lower prevalence of CI when compared to the more recent studies by Rao[45] and Ming-Leung et al.[46] The change in landscape of learning, work and leisure environments during the period 2001 and 2019 may be a possible reason for this. The rise of the internet, smartphone technology and the digitisation of reading material occurred during this period, which may be a contributing factor to an increased number of visual anomalies in a population that spends a significant amount of time interacting with e-devices.

Both clinical and non-clinical populations are compelled to use e-devices to keep up with technological advancements. These devices are commonly used at a near working distance of between 26 cm and 40 cm,[25] even closer with smart phones. Thus, it is logical to assume that e-device usage may pose just as much, or more, of a threat to the visual health of the vergence system as compared to traditional near work.

Convergence insufficiency in school-going children

The prevalence of CI amongst school-going children, aged from 6 years to 18 years old, is reported in Table 2.

Rouse et al.[32] investigated the prevalence of CI among children in grades five and six (9–13 years old) and found an 8.4% prevalence of low suspect CI, 8.8% of high suspect CI and 4.2% of definite CI. Clinically significant CI (high suspect CI and definite CI) was found to have a 13% prevalence.

Almost two decades ago, Borsting et al.[27] investigated the association between CI and accommodative insufficiency (AI) and their associated symptoms in school-aged children between 8 and 15 years old. About 45% of children presented with a binocular vision anomaly, of which 4.6% were diagnosed with three sign CI and 12.7% with two sign CI. It was also found that the children with three sign CI and those with AI scored higher on the Convergence Insufficiency Symptom Survey (CISS), compared to those with normal binocular vision, suggesting that three sign CI and AI are associated with an increased number of symptoms in school-aged children.

Shin et al.[47] investigated the prevalence of non-strabismic disorders in primary school children (aged 9–13 years old) and the association this has to academic achievement. The study found that 71.9% of the study population presented with some form of binocular disorder. Using the guidelines laid out by

the Convergence Insufficiency Treatment Trial (CITT),[32] the presence of four or more clinical signs was used to diagnose CI. A prevalence of 28% was observed among participants; additionally, a significant relationship was found between non-strabismic disorders and academic performance. This suggests that the presence of binocular anomalies has a significant negative effect on the lives of young children.

Wajuihian et al.[48] studied a secondary school population residing in a semi-rural part of South Africa and found that common CI was observed in 3.2% of the study population. Using the CIRS classification system, CI was graded as being low suspected CI (16%) and definite CI (1.6%). The follow-up study by Wajuihian et al.[49] in 2015 comprised two-thirds of the study population as being from an urban area and the remainder from a rural district. The study found that 32.9% of the students presented with a vergence anomaly, encompassing low suspected CI (11.8%), high suspected CI (6%) and definite CI (4.3%). Clinically significant CI represented a 10.3% prevalence.

Darko-Tayki et al.[50] studied school-going children (aged 12–17 years old) in Ghana, using a questionnaire to identify symptomatic school children followed by clinical assessment of those children. The study found an 8.6% prevalence of CI using the presence of at least 80% of the clinical signs (as outlined by Schiemann) to diagnose the disorder.[2]

Davis et al.[51] investigated the prevalence of CI and AI among American children in grades three to eight, and assessed the visual symptoms experienced by the children. The study classified CI as either being common CI, that is, presenting with two clinical signs or classic or clinical CI which presents with three or more signs. The overall prevalence of CI was found to be 31.4%; however, symptomatic CI was found to be 6.2%. Symptomatic CI took into consideration the CISS scores found during testing. The study location and time period are at the centre of the 4IR in a developed country with greater access to e-devices. This may have unwittingly provided indirect evidence of CI in a digital era.

A similar study sought to investigate the prevalence of non-strabismic binocular anomalies among school-going children (aged 7–17 years old) in urban and rural Tamil Nadu in 2017.[28] The study found a high prevalence of vergence disorders among participants, 31.5% and 29.6% from urban and rural populations respectively displayed signs of binocular anomalies. Convergence insufficiency was the most common disorder with a 16.5% prevalence in the urban group and a 17.6% prevalence in the rural group.

Hassan et al.[52] investigated the prevalence of CI among Sudanese secondary school students. A prevalence of 7.8% was observed in the population, with CI being diagnosed by either the presence of two clinical signs or just one clinical sign. A higher prevalence of CI was found among males, in agreement with other studies.[26,32,49,53]

Nunes et al.[44] studied Portuguese primary school children in 2019 to determine the frequency of CI among this population.

TABLE 2: Convergence insufficiency in school-going children.

Study	Year	N	Age (years)	Criteria to diagnose CI	Prevalence
Rouse et al.[32]	1999	453	9–13	CIRS Criteria:	
				• Low suspect CI (Near XOP and one clinical sign)	Low suspected – 8.4%
				• High suspect CI (Near XOP and two clinical signs)	High suspected – 8.8%
				• Definite CI (Near XOP and three clinical signs)	Definite – 4.2%
					Clinically significant CI: 13%
Borsting et al.[27]	2003	392	8–15	Two sign CI	Two sign CI – 12.7%
				Three sign CI	Three sign CI – 4.6%
					Overall prevalence: 17.3%
Shin et al.[47]	2009	114	9–13	Four clinical signs:	28%
				• NPC equal to or greater than 6 cm	
				• Near XOP greater than the distance XOP by 4 PD or more	
				• Low positive fusional reserves	
				• Normal accommodative amplitudes as per Hofstetter's formula	
Wajuihian et al.[48]	2013	65 (Secondary school population)	13–19	CIRS criteria:	
				• Low suspect CI (Near XOP > Distance XOP plus one other clinical sign)	Remote NPC – 3.2%
				• High suspect CI (Near XOP plus two clinical signs)	Low suspect CI – 16%
				• Definite CI (Near XOP plus three clinical signs)	Definite CI – 1.6%
					Clinically significant CI: 1.6%
Wajuihian et al.[49]	2015	1201	13–19	CIRS criteria:	
				• Low suspect CI (Near XOP > Distance XOP plus one other clinical sign)	Low suspect CI – 11.8%
				• High suspect CI (Near XOP plus two clinical signs)	High suspect CI – 6%
				• Definite CI (Near XOP plus three clinical signs)	Definite CI – 4.3%
					Clinically significant CI: 10.3%
Darko-Tayki et al.[50]	2016	627	12–17	Two or more symptoms (on the asthenopia survey)	8.6%
				The presence of five clinical signs including:	
				• Moderate to large near XOP	
				• Low positive fusional reserves	
				• Receded NPC	
				and *two* of the following:	
				Low NRA, Low MEM, Low AC/A ratio or failing binocular accommodative facility with +2.00 DS (less than 3 cpm)	
Davis et al.[51]	2016	484	3rd–8th graders 11.67 ± 1.81 years	Three clinical signs, namely:	31.4%
				• Near XOP > Distance XOP by 4 PD	
				• Receded NPC	
				• Low positive fusional reserves	
Hussaindeen et al.[28]	2017	920	7–17	Two or more clinical signs present	Urban group – 16.5%
					Rural group – 17.6%
Hassan et al.[52]	2018	4211	15.5 ± 2.5 years	Two sign CI	Two sign CI – 6.12%
				One sign CI	One sign CI – 1.68%
					Overall prevalence: 7.8%
Nunes et al.[44]	2019	292	10–14	Low suspect CI	6.8%
				High suspect CI	
				Definite CI	
Atowa et al.[54]	2019	537	10–16	CIRS criteria:	
				• Low suspect CI (Near XOP > Distance XOP plus one other clinical sign)	Low suspect CI – 9.6%
				• High suspect CI (Near XOP plus two clinical signs)	High suspect CI – 5.8%
				• Definite CI	Definite CI – 4.1%
					Clinically significant CI: 9.9%
Ming-Leung et al.[53]	2019	928	13–19	Grading system encompassing three sign CI, two sign CI and one sign CI	Three sign CI – 2.7%
					Two sign CI – 12.8%
					One sign CI – 32.6%
					Clinically significant CI: 15.5%

CIRS, Convergence Insufficiency Reading Study; CI, convergence insufficiency; XOP, exophoria; NPC, near point of convergence; NRA, negative relative accommodation; PD, prism dioptres; cpm, cycles per minute; MEM, monocular estimation method retinoscopy; AC/A, accommodative amplitude to accommodation; DS, dioptre sphere.

The study comprised of primary school children aged between 10 and 14 years old. The study categorised CI as being either low suspect, high suspect or definite CI and a 6.8% prevalence of clinically significant CI was noted.

Atowa et al.[54] conducted a similar study, and sought to develop a vergence profile of Nigerian school children aged between 10 and 16 years old. Clinically significant CI was found to have a prevalence of 9.9%. The authors employed the CIRS classification system, classifying CI as being either low suspect CI, which showed a 9.6% prevalence, high suspect CI (5.8%) or definite CI (4.1%). Clinically significant CI was found to have a prevalence of 9.9%.

Ming-Leung et al.[53] investigated the prevalence of CI among urban high school students (aged 13–18 years old) in urban China in 2019. The study classified the disorder according to the number of signs students presented with. Prevalence's of 2.7% (three sign CI), 12.8% (two sign CI) and 32.6% (one sign CI) were observed. The study also explored links to gender and refractive error and concluded that hyperopes were most likely to present with the disorder, followed by emmetropes. Males were also found to be more at risk compared to females. No possible reason was postulated by the authors; however, other similar studies noted that gender associations varied.[26,32,49]

Direct comparisons of the observed prevalence's across all the above-mentioned studies may prove challenging as they all make use of different diagnostic criteria. However, the notable prevalence of CI across each study raises a definite concern.

Wajuihian et al.[48,49] and Rouse et al.[32] made use of the CIRS criteria to diagnose CI. Both studies conducted by Wajuihian et al.[48,49] made use of the same age range and demographics of the participants. As such, the results are largely comparable. The 2013 study[48] noted a very low prevalence of clinically significant CI, whereas the 2015[49] study observed a higher prevalence. This may be owing to population differences, with the 2013[48] study employing a semi-rural population and the 2015[49] study including both urban and rural populations. Urban populations have intensive near demands, including laptop computer use and smartphone exposure. These devices are used at a near working distance, as such they can affect the vergence system.

The 2013[48] study also noted a higher prevalence of low suspected CI (16%) when compared to the follow-up study in 2015,[49] which noted an 11.8% prevalence. Differences were also noted in the prevalence of definite CI, with a lower prevalence being observed in the 2013 study compared to the follow-up study. These differences may be owing to the large difference in sample size between the two studies. Nonetheless, this proves that CI is prevalent among this population and when one considers that these are high school students, who understandably spend a great deal of time studying and focussing at near, it raises the question as to whether the near work demand may be negatively influencing their vergence status. Although the use of e-devices was not explored, the era the study was performed in must factor in this influence.

The study conducted by Rouse et al.[32] employed the same age range and largely similar diagnostic criteria as compared to the study by Shin et al.[47] It is noteworthy that the study by Shin et al.[47] found a much higher prevalence of CI as compared to Rouse et al.[32] The period prior to the 2000s was before electronic devices gained their popularity, as such, the near demand experienced would be much less compared to that experienced today. This may explain the lower prevalence observed by Rouse et al.[32] As represented by the more recent study,[47] it appears as though increased exposure of e-devices in younger populations may contribute to a higher prevalence of near disorders. Recent studies have noted that young children experience significant asthenopia caused by their excessive e-device usage.[55]

Ming-Leung et al.[53] made use of the same age range as that of Wajuihian et al.;[48,49] however, the prevalence of clinically significant CI in the study by Ming-Leung et al.[53] was significantly higher than that observed by Waijuihian et al.[48,49] A possible cause for this may be the population being studied. Wajuihian et al.[48,49] included participants from a semi-rural area whereas Ming-Leung et al.[53] were based in a more urban setting. Participants in urban areas are exposed to more intensive near vison requirements when compared to their counterparts from rural areas. It must also be noted that the study conducted by Ming-Leung et al.[53] was conducted most recently (2019). During this time period, significant progress has been made in the field of smartphone technology and hand-held e-devices, so much so that e-devices are now a commonplace in many urban households.[5] Recent studies have shown that this increased exposure is causing significant asthenopia among school-going children,[55,56] and have associated CI with the increased visual demand brought on by intensive studying for school work.[44]

Borsting et al.[27] and Hussaindeen et al.[28] both employed similar diagnostic criteria with comparable age ranges. However, Hussaindeen et al.[28] considered participants in both an urban and a rural setting whereas Borsting et al.[27] made no distinction between population groups. The observed prevalence of CI was higher for Hussaindeen et al.[28] The time of investigation also differs with the study by Hussaindeen et al.[28] being conducted most recently (2017). This again may alert one to the influence of e-devices among the study populations, which may compound their near demands of the Hussaindeen[28] study. Darko-Tayki et al.[50] implemented the most stringent diagnostic criteria among participants, as such, the expected prevalence of CI was relatively lower in this population despite the age group being tested being comparable to other studies.[48,49] Although no possible reasoning explains the relatively high prevalence of CI, considering the near demand experienced by school-going children today, including leisure activities such social media use, the effect on the vergence system cannot be ignored.

The studies by Davis et al.,[51] Hassan et al.,[52] Nunes et al.[44] and Atowa et al.[54] all made use of similar diagnostic criteria and were conducted among a similar time period. The age ranges employed by Nunes et al.[44] and Atowa et al.[54] were most similar; however, a higher prevalence of CI was noted by Atowa et al.[54] It was noted by Nunes et al.[44] that their observed prevalence was much lower compared to other prevalence studies in developed countries, although no possible reason for this was postulated.

The study conducted by Davis et al.[51] noted the highest observed prevalence of CI. The authors acknowledged that the results were much higher compared to other studies, and postulated that since the selection criteria allowed students from any grade to be eligible for the study; those were already symptomatic may have been more likely to enrol. Another factor may be that the study location is the United States, where many children have access to e-devices and other mobile technologies. Studies conducted in other developed countries have shown an increase in asthenopia among adolescents, which is shown to be related to their e-device usage.[57,58]

All the above-mentioned studies noted a significant prevalence of CI among school-going children. Recent evidence shows that CI has been associated with the intense visual demand required of schooling children,[44] with Wajuihian et al.[48] also noting that near work adversely affects the visual system. E-device use among young children has become so commonplace, the added near demand from using these devices for a significant portion of the day[55,59] may be adversely affecting the visual system. Nonetheless, the collective findings of the studies are concerning. School-going children have significant near visual demands just from their studying. When considering that many[44,45,46,47] of the studies included urban populations, the possible influence of e-device use must be factored.

Modern definitions of near work encompass e-devices and screen time exposure; therefore, when observing the prevalence of CI and associations to near work, it is imperative to also study the visual effects of digital devices.

Primary school children: An emerging concern?

Ritty et al.[60] conducted a study wherein the ergonomic conditions of grade three and four classrooms were observed. Among other factors, it was noted that up to 75% of the learners' time is dedicated to near work activities. This is in contradistinction to the assumptions that younger children are not at risk for vergence disorders, as evidenced by the historical interest in adults. Extensive near work is known to affect the visual system, thus this review supports the philosophy that binocular vision research should include much younger populations.

Metsing et al.[61] attempted to determine the binocular status of grade three and four children by investigating the prevalence of vergence and accommodative disorders in an urban-based school population aged between 8 and 13 years old. The study found binocular anomalies to be more common in young children than previously thought with 17% of the children presenting with a remote NPC and 21.9% with poor vergence facility. This raises further concerns as binocular disorders in children can influence their academic performance.[47]

Junghans et al.[56] investigated the prevalence of asthenopia in a population of school-going children in 2020. The study included children in grades six to nine and, by making use of the Convergence Insufficiency Symptom Survey (CISS), evaluated whether the children experience any significant degree of asthenopia. The results showed that 45% of the study population presented with asthenopia. The authors agreed that this was much higher when compared to other studies and postulated that it could be as a result of the increased uptake of e-devices. These findings are particularly concerning as asthenopia associated with near tasks will act as a deterrent to learning and completing school work. Additionally, undiagnosed vergence disorders may present as asthenopia.[62]

Urbanisation, e-devices, convergence insufficiency and learning

Convergence insufficiency has proven to be a highly prevalent disorder in the general population, which has significant implications in our society. Among secondary school and university students, it is understandable for there to be a higher than average prevalence due to the increased near demand resulting from long hours of studying.[42] One must consider the fact that university students often make use of e-devices to complete their coursework and supplement their learning process. The visual effects of e-devices may be a contributing factor to the increasing prevalence of CI.

Studies in this review have shown CI to be prevalent among younger school children. This is alarming as children are engaging more with e-devices. It is possible that increased screen time, and thus the increased near demand, may contribute to a poorer vergence status of this vulnerable population. Studies[28,49] have noted similar prevalence's of vergence disorders among urban participants which may be as a result of intensive near work. This supports the premise that the presence of e-devices in sub-urban settings may be influencing the visual status of the population. However, Hussaindeen et al.[28] also observed an increased prevalence of CI in a rural locale. The changing technological landscape may not discriminate rural settings as previously thought, thus the discounting of surveillance in this setting should not be ignored.

Darko-Tayki et al.[50] reinforced young children's susceptibility to binocular anomalies by showing they are conscientious of their symptoms, thus dispelling the notion that younger children are unreliable and unspecific in judging how they feel.[30] Although no reason for the high observed prevalence

of CI was provided and no link to e-devices were explored, the study setting being a metropolitan area may also suggest widespread e-device use.

A recent study by Arif et al.[62] investigated the prevalence of CI with a direct focus on smartphone use. The study considered participants who were asthenopic after exposure to smartphones and found a 94% prevalence of CI. The study considered a very broad age range, ranging from 10 to 25 years old. This indicates that CI is a problem that affects both younger and older people equally. Additionally, 90% of the study population presented with asthenopia prior to being diagnosed. This is significant as many other current studies have noted that younger children experience significant asthenopia following e-device use.[55,56,59]

The COVID-19 pandemic has resulted in a change in lifestyle for many. Employers, schools and higher education facilities opting to work from home have resulted in a significantly increased near demand. Additionally, individuals who isolate or quarantine as a result of contracting the virus may find themselves interacting with e-devices more frequently in order to pass the time. A recent study by Mon-Lopez et al.[63] investigated CISS scores among people who were in COVID-19 isolation and correlated this to their physical activity. A 43% increase in CISS scores was noted during the isolation period. Additionally, screen time exposure increased by 44.01% whilst physical activity decreased during the isolation period. Given that the CISS is a valid diagnostic tool used to diagnose symptomatic CI,[64] the study shows that extensive e-device use may affect the vergence system and increase the likelihood of developing CI.

Children today have very specific and intense near visual demands. Near work is a significant presence in their schooling environment, which we already know to be harmful to the visual system of adults. Their current lifestyle is dominated by technology and exposure to smart devices, this may be placing additional demands on the vergence system,[4] as shown by the above studies.[62,63] The evidence regarding young children and e-devices in this review is concerning and serves as a reminder that more studies need to be conducted on the visual and ocular-motor effects associated with e-devices in younger populations.[47] Rehabilitation is necessary at this age, as they are the future workforce of the world, which most likely be white-collar work as artificial intelligence is aiming to replace repetitive tasks such blue-collar work during the 4IR.

The visual effect of near work and digital eye strain in children

Smart device usage comprises a significant proportion of near work in modern society. The global penetration of smart device usage in 2018 was measured at 34.7%.[4] Considering that reading print on traditional paper is not the same as reading off a screen, one must remain mindful of the visual effects produced by prolonged e-device use, otherwise known as the effect of device screen time (DST).[6,11] Digital eye syndrome has a prevalence of between 20.0% and 40% among e-device users.[12,65,66] Some studies[8] report it to be as high as 68.5% and 69.0%. Digital eye syndrome is thought to be associated with both the short term (acute) and the long term (chronic) effect of sustained near focus on the accommodative and vergence systems. The dry eye symptoms that many users experience are due to drying out of the anterior ocular surface that is induced by sustained focus on a digital screen and a reduced blink rate.[10] Studies show that 1 hour of e-device usage among young adults increased eye strain and blur by up to five times.[67,68] Internal DES is due to disturbances of the accommodative or vergence system, or a combination of the two, thus it is unquestionable that consistent e-device usage can negatively impact the visual system.[10]

Another contributing factor to DES is the presence of blue light emitted from LED screens that are used in modern day digital devices. Blue light, or short wavelength light, consists of wavelengths of between 400 nm and 500 nm and has been shown to be damaging to the internal ocular structures.[69] Usually, much of the blue light is filtered by the ocular structures, such as the cornea and the crystalline lens.[70] However, certain populations are more at risk for exposure to blue light, such as aphakic and pseudophakic individuals, who lack the protection of the crystalline lens. Children are also vulnerable due to the transparency of their crystalline lens.[14] Exposure to blue light has been shown to exacerbate symptoms of DES among sufferers.[71]

Studies have investigated the effectiveness of blue blocking filters to manage symptoms of DES.[9,72,73,74] Whilst some studies[9,73] have shown there to be an improvement in reported symptoms, others[74] disagree and as such there is some debate as to their usefulness in symptomatic management.

Increased amounts of DES among young children were also found to reduce the diameter of the retinal microvasculature. It is concerning that a single hour of screen time was found to induce a similar arterial appearance as a 10 mmHg increase in systolic blood pressure.[75] Evidence[18,19,20,21,22] also shows that exposure to e-devices among young children is significantly associated with an increasing incidence of myopia and may contribute to myopia progression in young children.[76] However, a systematic review by Lanca et al.[23] suggested screen time is not associated with prevalence and incidence of myopia. However, majority of the studies used were from Asia and with the inherently high prevalence of myopia in those populations, the results may be an inaccurate representation. Thus, if non-Asian populations with no inherent myopia predispositions were used, would this challenge the findings? The author did caution that the findings were mixed and noted a need for more studies focussing on the visual effect of e-devices, given the increasing penetrance of e-devices in our society.

Children may be more susceptible to developing symptoms of DES compared to adults. Symptoms occur when the visual demand of the task exceeds the visual ability to comfortably perform the task.[16] Considering that young children have an extremely malleable visual system, the strain induced by being unable to adequately compensate for the near demand may induce visual and/or binocular problems in years to come. The present-day reality is one where E-learning technologies are being integrated into existing learning systems. This modality is gaining popularity; however, the visual effects of E-learning need to be considered. No study has considered the direct visual effects of E-learning and prolonged e-device use. Evidence-based research investigating binocular status with a focus on DES in children is absent. This gap in knowledge needs to be addressed as the digital revolution makes its way into the world of children.

Limitations

A possible limitation of the current review that the studies included in this review lacked a standard diagnostic criterion for CI. Some used extremely stringent criteria whereas other studies applying a more liberal approach with only a single sign diagnostic criterion. These veritable differences affect coherence of reporting in diagnosing CI and lead to significant differences in the observed prevalence of the disorder in different populations. All the studies included in this review considered either CI or electronic devices, and one study considered CI and mobile phone use in a clinical population. Studies do indicate an increase in asthenopia following e-device use in young children, and another study correlates asthenopia after exposure to e-device with CI. However, no study mapped the direct visual impact of e-device usage and CI in young children. The evidence of this review may however serve as indirect associations for our observations.

Recommendations

This review recommends more studies focussing on vergence disorders, specifically CI, be conducted on primary school children. Also, future researchers should consider the visual status of younger children with a direct focus on the impact of e-device usage, which constitutes as near work. Being that schools are moving towards a more technologically savvy model, it is imperative to understand both the short-term and the long-term effects of prolonged e-device exposure and DES. Future studies should explicitly declare the diagnostic criteria employed to diagnose CI by utilising an accepted clinical set of criteria and reliable clinical diagnostic methods. This may allow for repeatability in future studies and allow for accurate comparisons between population age groups and demographics.

Conclusion

Convergence insufficiency has proven to be a common disorder among both young children and adult populations. It is highly prevalent in those individuals who spend a significant portion of time consumed by near tasks such as schooling and university populations. With many schools implementing E-learning models, there is a considerable need for research studies to focus on the visual effects of prolonged near focus with e-devices in younger populations. Poor vision or binocular anomalies including CI among children may lead to difficulty in other areas of their lives including their academic performance. Determining whether or not the prevalence of these disorders among school-going children is linked to their e-device exposure will give clinicians a greater understanding as to how to manage and treat the condition in the context of their lifestyle demands. With such a high rate of technological uptake in society, medical professionals need to manage the health impact of our increasingly tech-infused lifestyle effectively and efficiently. Studies of this nature are of paramount importance if we are to adapt to the new technological times where the world, including young children, are forced to survive and thrive using e-devices.

Acknowledgements

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