Smartphone overuse and visual impairment in children and young adults: a systematic review and meta-analysis

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Abstract

Background: Smartphone overuse has been cited as a potentially modifiable risk factor that can result in visual impairment. However, associations between smartphone overuse and visual impairment have not been consistently reported.

Objective: The aim of this systematic review is to determine the association between smartphone overuse and visual impairment, including myopia, blurred vision, and poor vision, in children and young adults.

Methods: We conducted a systematic search in the Cochrane Library, Pubmed, EMBASE, Web of Science Core Collection, and ScienceDirect since the beginning of the databases to June 2020. Fourteen eligible studies (ten cross-sectional studies and four controlled trials) were identified, which included a total of 27110 subjects with mean ages ranging from 9.5 to 26.0 years. We used a random-effects model in the ten cross-sectional studies ($n = 26962$) and a fixed-effects model in the four controlled trials ($n = 148$) to combine odds ratios (OR) and effect sizes (ES). The $I^2$ statistics was used to assess heterogeneity.

Results: A pooled OR of 1.05 (95% CI: 0.98, 1.13; $p = 0.159$) from cross-sectional studies suggests that smartphone overuse is not statistically significantly associated with myopia, poor vision, or blurred vision, however these visual impairments together are more apparent in children (OR = 1.06, 95% CI: 0.99, 1.14; $p = 0.087$) than in young adults (OR = 0.91, 95% CI: 0.57, 1.46; $p = 0.707$). In all the controlled trials, the smartphone overuse groups showed worse visual function scores compared with the less-use groups. The pooled ES is 0.76 (95% CI: 0.53, 0.99) and statistically significant ($p < 0.001$).

Conclusions: Our results indicate that longer smartphone use may increase the likelihood of ocular symptoms including myopia, asthenopia, and/or ocular surface disease, especially in children. Thus, regulating use time and restricting the prolonged use of smartphones may prevent ocular and visual symptoms. Further research on the patterns of use, with longer
follow-up on the longitudinal associations will help inform detailed guidelines and recommendations for smartphone use in children and young adults.

KEYWORDS

visual impairment; smartphone; mobile phone; overuse; child; young adult; systematic review; meta-analysis
**Introduction**

The use of smartphones has been increasing rapidly since their introduction in the late 2000s [1]. In 2019, the global smartphone penetration had reached to about 41.5% of the global population [2]. Notably, the number of smartphone users in China was around 700 million in 2018, accounting for half of the Chinese population [3]. Data also showed that more than 80% of people in the United Kingdom owned or had ready access to a smartphone in 2019, with a significant increase from 50% in 2012 [4]. Furthermore, more than 90% of young people between 16 and 34 years old in the United Kingdom owned a smartphone [4].

With the continuous rise in youth’s digital media consumption, ocular problems have also seen a dramatic increase. A large population is suffering from visual impairment, especially in Asian countries, due to its rapidly increasing prevalence and younger age of onset [5-8]. It has been estimated that 49.8% (4.8 billion) and 9.8% (0.9 billion) of the global population will have myopia or high myopia by the year 2050 [9]. A recent study indicated that, about sixty years ago, only 10 – 20% of the Chinese population was shortsighted, but the percentage has been up to 90% of teenagers and young adults in 2015 [10]. Consistently, a school-based, retrospective, longitudinal cohort study ($n=37424$) found that the prevalence of myopia significantly increased from 56% in 2005 to 65% in 2015 [8].

Therefore, smartphone overuse among children and young adults has raised crucial concern in the society [11-13]. Several studies found an increased use of digital devices in children aged 2 – 11 years old [14, 15]. For example, a study of children aged 9 – 11 years old from 12 countries showed that 54.2% of the children exceeded proposed screen time guidelines ($\leq 2$ hours per day) [15]. Compared with older people, greater risks of the undesirable consequences in children and young adults have been reported because they have less self-control in smartphone use [11]. A cross-sectional study ($n = 2639$) indicated that 22.8% of teenagers were smartphone addiction users, which was related to hypertension [16]. Another
research showed that the users of mobile devices spent > 20 hours weekly using email, text messages, and social networking services, indicating the heavy reliance on smartphones in their communication with other people [17]. Overall, smartphone overuse may result in significant harmful physical, psychological, and social consequences [18, 19].

Some experimental studies indicate that long time use of smartphone plays a key role in visual impairment, increasing the likelihood of poor vision [20-22]. For instance, a prospective clinical study \((n = 50)\) showed that smartphone use for 4 hours resulted in a higher ocular surface disease index than those at baseline [20]. Kim et al found that the increase of ocular symptoms extended to the general population, especially in adolescents, after the expansion of smartphone use [23]. However, there are also studies that reported the lack of evidence for such association [24]. For example, a cross-sectional study \((n = 1153)\) using stratified random cluster samples did not find a statistically significant association between smartphone use time and myopia [25]. Similarly, a research in Ireland \((n = 418)\) indicated that smartphone use time was not a risk factor for myopia [26]. Also, Toh et al found that smartphone use time was associated with increased risk of visual symptoms (i.e. blurring of vision, dry eye), but decreased odds of myopia [27].

Although there has been increased concern about impaired vision by smartphone overuse, existing quantitative evidence about the relationships between excessive smartphone use and visual impairment is equivocal. It is essential to confirm and quantify whether excessive smartphone use may result in visual impairment, especially in children and young adults.

The aim of this study is to conduct a systematic review to summarize the existing evidence on the associations between smartphone overuse and visual impairment in children and young adults, which may further guide potential interventions to reduce the harmful impact of smartphone overuse on vision in the susceptible subpopulation group.


**Materials and Methods**

**Data sources and search strategy**

To carry out the systematic review and meta-analysis, we used a protocol that was constructed in line with the standard criteria, the Preferred Reporting Items for Systematic Reviews and Meta-Analysis (PRISMA) [28] and the Meta-analysis of Observational Studies in Epidemiology (MOOSE) [29].

A systematic search was carried out in Pubmed (the United States National Library of Medicine), Embase (Wolters Kluwer Ovid), Web of Science Core Collection (Clarivate Analytics), ScienceDirect (Elsevier), and Cochrane library (John Wiley & Sons, Ltd.) for observational and experimental studies that investigated smartphone overuse or addiction in children (age <18 years) or young people (age <40 years), and its associations with impaired visual function, such as myopia, poor vision, or blurred vision. To minimize publication bias, we also searched for additional studies in grey literature sources including Virtual Health Library (http://bvsalud.org/en/), NARCIS (https://www.narcis.nl/), Grey literature report (http://greylit.org/), and Open grey EU (http://opengrey.eu/). The search was limited in the publications published in English.

Free text and the Medical Subject Headings (MeSH) terms were used for the search, including: phone, smartphone, mobile/cell/cellular phone, electronic device, use, use time, screen time, overuse, addiction, eye, visual acuity, vision, vision screening, eyesight, myopia, myopic refraction, shortsighted/nearsighted/short sight, near sight, refraction errors, /ocular/health effect, optic, blind, ophthalmology, optometry, retina, ametropia/amblyopia symptom, visual assessment, and visual problem etc. (Supplemental material 1). We included all the observational studies and controlled trials (randomized or non-randomized), addressing smartphone use and visual impairment in human since the beginning of the databases to June
2020. Furthermore, manual retrieval was performed afterwards to ensure the inclusion of the latest literature.

**Inclusion and exclusion criteria**

All observational and experimental studies were included if they have fulfilled the following criteria:

1. All original studies have examined the use of a smartphone (and/or mobile phone) and eyesight, including population-based longitudinal studies, cohort studies, case-control studies, cross-sectional studies, and controlled clinical trials;

2. The participants are children age $\leq 18$ years or young people with age $\leq 40$ years; the young adulthood in the study was defined as the developmental stage of those who are between 18 years old and 40 years old [30, 31];

3. The frequency or time of smartphone use (in minutes or hours, or per day or per week, et al.) have been reported;

4. The endpoint of interest is the incidence of visual impairment or decline, including myopia, poor vision, blurred vision, various visual function scores indicating impaired vision, and/or other unspecific visual impairments;

5. Vision measurements of the groups that may be used to calculate effect size (ES) of visual impairment, or odds ratio (OR) for the risk of visual impairment have been reported, as well as the associated 95% confidence interval (CI) or other data to estimate the variance or accuracy (such as standard error) were reported.

Studies were excluded if they:

1. Are narrative reviews, editorial papers, commentaries, letters, or methodological papers;

2. Have evaluated visual function, or no reliable/relevant estimates for smartphone use;
(3) Have no reference or control group included in the analysis;

(4) Are animal studies.

Data extraction

After the systematic search of the relevant articles in the databases, two investigators (J.W. and M.L.) embarked on screening and identification of potentially relevant abstracts independently. For any disagreements that occurred between the two investigators regarding the eligibility of a study, there was a thorough discussion or advice from an academic expert (Y.C.). Later, articles for selected abstracts were downloaded and data extracted by J.W. and Y.C. independently by use of a standardized form in Microsoft excel. Data extracted were compared and summarized to have one final document on which analysis was conducted. The information extracted included: name of the first author, year of publication, study design, duration of study, country that the study was conducted in, eyesight measurement, smartphone use time, smartphone use frequency, sample size, incidence cases with impaired vision, outcome ascertainment method, OR or ES and the associated 95% CI, and statistical analysis method used.

Study quality assessment

The Joanna Briggs Institute (JBI) Critical Appraisal Checklist for Analytical Cross Sectional Studies, JBI Appraisal Checklist for Quasi-Experimental Studies, and JBI Critical Appraisal Checklist for Randomized Controlled Trials were used to assess the quality of the studies included in the meta-analysis [32]. J.W. and Y.C. assessed the quality of the articles independently then the final assessment was achieved upon discussion (Supplemental material 2, Tables S1 – S3).
Statistical analysis

For studies that did not report OR, OR was calculated using the numbers of cases with and without visual impairment of the reference/control group and overuse group. For studies that measured visual impairment using continuous variables, ES was calculated as the difference between the means divided by the pooled standard deviation (SD) [33]:

\[
ES = \frac{Mean_{group1} - Mean_{group2}}{Pooled \ SD} = \frac{Mean_{group1} - Mean_{group2}}{\sqrt{(n_1 - 1)S_1^2 + (n_2 - 1)S_2^2}} \sqrt{\frac{n_1 + n_2 - 2}{n_1 + n_2}}
\]

where \( n_1, S_1 \) and \( n_2, S_2 \) are sample size and standard deviation for group 1 and group 2, respectively.

A positive ES indicates a worse visual function. Heterogeneity of the included studies was investigated using \( I^2 \) statistics[34]. \( I^2 > 30\% \) was considered moderate heterogeneity while \( I^2 > 50\% \) was considered substantial heterogeneity [35]. A p-value < 0.05 from the non-central chi-squared test for heterogeneity was considered statistically significant[36]. Contribution of each study to the heterogeneity and their influence on the pooled OR or ES was presented using Baujat plot [37]. The pooled OR with corresponding 95% CI were calculated using random effect models because heterogeneity presented among the studies, and presented using forest plot [38]. The possibility of publication bias was assessed by the combination of Egger’s test and visual inspection of funnel plot [39].

Subgroup analysis was performed for cross-sectional studies by outcome of visual impairment (myopia, poor vision, or blurred vision) and mean age of the subjects (children, mean age ≤ 18 years, or young people, mean age > 18 and ≤ 40 years). Leave-one-out (LOO) analysis to investigate the influence of a single study on the pooled effect was also performed as sensitivity analysis [40].

A two-sided p-value < 0.05 of the pooled estimates was considered statistically significant unless otherwise specified. All the analysis was performed in R 4.0.0 (the R Foundation for
Statistical Computing, Vienna, Austria) using packages *meta* 4.12-0 [41] and *dmetar* 0.0.9000 [42].

**Results**

**Characteristics of the studies**

In total, 1961 articles were obtained from all the databases. After removing the duplicates, 1796 articles remained, and 121 of them were considered relevant for the meta-analysis after screening of the titles and abstracts. After screening full-text of the 121 articles downloaded, 14 articles met our inclusion criteria. These included ten cross-sectional studies and four controlled trials, which consisted of 27110 participants with mean ages ranging from 9.5 to 26.0 years. The flowchart of article searching and screening is shown in Figure 1. The ten cross-sectional studies addressed incidents of myopia [24-27, 43], blurred vision [44-46], poor vision and other unspecified visual impairments [23, 27, 44, 47]. In our analysis, those unspecified visual impairments were treated as poor vision. There are two studies [27, 44] that addressed two visual impairment outcomes, and each outcome was treated as a single study in the meta-analysis. The four studies that used the controlled trial design addressed ocular surface disease index score [20], asthenopia score [21], oculomotor function [48], and viewing distance [22]. A more detailed summary of characteristics of the included studies is reported in Table 1.
Figure 1. PRISMA flow diagram for screening and selection of articles on smartphone overuse and visual impairment in children and young adults.
Table 1. Characteristics of the included studies

| Frist author, year | Country        | Study design         | Age of participants (years) | Sampling method            | Sample Size | Response rate | Exposure and type of measure | Outcome and type of measure | Main results                                                                 |
|-------------------|----------------|----------------------|----------------------------|----------------------------|--------------|---------------|------------------------------|----------------------------|--------------------------------------------------------------------------------|
| Küçer, 2008[45]   | Turkey         | Cross-sectional study| NA (university students)   | Convenience sample         | 229          | 100%          | Time of mobile phone possessions (MP); Q | Blurred vision; Q            | MP time ≤ 2 years: 8.8% (4/45) MP time > 2 years: 27.2% (50/184)             |
| Toh, 2019[27]     | Singapore      | Cross-sectional study| 13.3 ± 2                   | Matrix stratified sample   | 1884         | 93.78%        | Time of smartphone use (per hour); Q | 1) Myopia; Q 2) Poor vision/visual impairment; Q | 1) OR = 0.97 (95% CI: 0.94, 0.99); 2) OR = 1.05 (95% CI: 1.02, 1.08)          |
| Merrie, 2019[47]  | Ethiopia       | Cross-sectional study| 13.1 ± 2.8                 | Multistage sampling        | 601          | 95.09%        | Duration of mobile exposure; Q         | Poor vision/visual impairment; Objective assessment | Mobile phone use > 2 h/day: 6.6% (18/271) Mobile phone use ≤ 2 h/day: 7.5% (20/265) |
| Guan, 2019[43]    | China          | Cross-sectional study| 10.6 ± 1.15                | Randomly selected sample   | 19,934       | UK            | Time of smartphone use; Q             | Visual acuity; Objective assessment | Mobile phone use 1 h/day: 20% (117/584); Mobile phone use ≤ 1 h/day: 18% (3492/19350) |
| Kim, 2016[23]     | Korea          | Cross-sectional study| 15                         | Convenience sample         | 715          | 97.41%        | Time of smartphone use; Q             | Poor vision/Ocular symptom score; Q | Smartphone use > 2 h/day: 72% (260/360); Smartphone use ≤ 2 h/day: 52% (170/327) |
| Liu, 2019[24]     | China          | Cross-sectional study| 9.5 ± 2.1                  | A stratified cluster sample| 566          | 88.7%         | Time of smartphone use (per hour); Q | Myopia; Objective assessment | OR = 0.90 (95% CI: 0.57, 1.43)                                                   |
| Meo, 2005[46]     | Saudi Arabia   | Cross-sectional study| 26                         | Voluntary (response)       | 873          | 100%          | Use of mobile phone (duration)         | Blurred vision; Q            | Duration of calls > 0.5 h/day: 5%                                               |
| Study | Country | Design | Sample Size | Sample Method | Duration of calls | Duration of Smartphone use per day | Myopia | Myopia Assessment | Results |
|-------|---------|--------|-------------|---------------|------------------|------------------------------------|--------|------------------|---------|
| Alharbi, 2019[44] | Saudi Arabia | Cross-sectional study | 21.8±2.4 | Random sample | 605 | 93.1% (605/650) | 1) Poor vision; Q 2) Blurred vision; Q 1) > 3 h/day: 57.2% (270/472); ≤ 3 h/day: 45.9% (61/133); 2) > 3 h/day: 46.0% (217/472); ≤ 3 h/day: 57.1% (76/133) |
| Huang, 2019[25] | China | Cross-sectional study | 19.6±0.9 | Stratified random cluster sample | 1153 | 96.08% (1153/1200) | Durations of daily smartphone use; Q | Myopia; Objective assessment | > 3 h/day: 84.57% (296/350); ≤ 3 h/day: 88.03% (537/610) |
| McCrann, 2020[26] | Ireland | Cross-sectional study | 16.8±4.4 | Voluntary sample | 402 | 96.17% (402/418) | Time on phone (minutes/day); Q | Myopia; Q | OR = 1.026 (95% CI: 1.001, 1.051) |
| Antona, 2018[21] | Spain | RCT | 23.7±2.6 | Random sample | 54 | 100% | Smartphone reading in vs. Printed hardcopy reading | Asthenopia score; Q | 27.96±20.11 vs. 13.25±12.76 |
| Choi, 2018[20] | South Korea | CT | 26±3 | Nonrandomized sample | 50 | 100% | Smartphone use after 4 hrs vs. baseline | Ocular surface disease index scores; Q | 25.03±10.61 vs. 15.08±8.83 |
| Lee, 2019[48] | Korea | CT | 20 – 29 | Voluntary sample | 26 | 86.67% (26/30) | Smartphone use 20 minutes vs. 5 minutes | Oculomotor function; Q | 6.35±3.54 vs. 3.73±4.09 |
| Long, 2017[22] | Australia | CT | 21.5±3.3 | Voluntary sample | 18 | 100% | Using smartphone after 1 hour vs. baseline | Viewing distance; Objective assessment | 27.8±7.7 cm vs. 31 ±8.2 cm |

Q: questionnaire; RCT, randomized controlled trial; CCT, controlled trial
Association between smartphone overuse and incidence of visual impairment

The funnel plot of OR for the included cross-sectional studies appears symmetric (Figure 2). Although OR from two studies (Kim and Küçer) show a bit bias with other studies, no statistically significant publication bias was found by Egger’s test (p = 0.434).

Figure 2. Funnel plot with pseudo 95% confidence limit for cross-sectional studies

Statistically significant heterogeneity was present among the ORs on visual impairment incidence ($I^2 = 84\%, p<0.001$; Figure 3). Baujat plot indicates that Kim’s study contributed to the heterogeneity a lot while having few influences on the pooled OR (Figure 4). Overall, although the pooled OR shows that the odds of visual impairment is higher in the smartphone overuse group compared to the less-use group (OR = 1.05, 95% CI: 0.98, 1.13), the result is not statistically significant (p=0.159; Figure 3). None of the pooled ORs for specific visual impairment is statistically significant either in subgroup analysis. The pooled ORs for myopia,
poor vision, and blurred vision are 1.00 (95% CI: 0.95, 1.05), 1.40 (95% CI: 0.87, 2.23), and 1.21 (0.44, 3.28), respectively (Figure 3). In neither age subgroups the pooled OR is statistically significant, which are 1.06 (95% CI: 0.99, 1.14; p = 0.087) for children and 0.91 (95% CI: 0.57, 1.46; p = 0.707) for young adults.

| Study               | Odds ratio (OR) | OR     | 95% CI       | Weight |
|---------------------|-----------------|--------|--------------|--------|
| Myopia              |                 | 0.97   | [0.95; 1.00] | 25.1%  |
| Toh, 2019           |                 | 0.90   | [0.57; 1.43] | 2.1%   |
| Liu, 2019           |                 | 1.03   | [1.00; 1.05] | 25.2%  |
| McCrann, 2020       |                 | 0.75   | [0.51; 1.09] | 3.0%   |
| Huang, 2019         |                 | 1.14   | [0.93; 1.40] | 7.9%   |
| Guan, 2019          |                 | 1.00   | [0.95; 1.05] | 63.3%  |
| **Within group**    |                 | 1.00   | [0.95; 1.05] |        |
| (random effects model): |       |        |              |        |
| $l^2 = 71\%$, $\chi^2 = 13.59$ (p = 0.009) |     |        |              |        |
| Subgroup effect: z = -0.05 (p = 0.961) |     |        |              |        |
| Poor vision         |                 | 1.05   | [1.02; 1.08] | 24.9%  |
| Toh, 2019           |                 | 1.58   | [1.07; 2.32] | 2.9%   |
| Alharbi, 2019       |                 | 2.40   | [1.75; 3.30] | 4.1%   |
| Kim, 2016           |                 | 0.87   | [0.45; 1.69] | 1.1%   |
| Merrie, 2019        |                 | 1.40   | [0.87; 2.23] | 32.9%  |
| **Within group**    |                 | 1.40   | [0.87; 2.23] |        |
| (random effects model): |       |        |              |        |
| $l^2 = 90\%$, $\chi^2 = 30.44$ (p < 0.001) |     |        |              |        |
| Subgroup effect: z = 1.39 (p = 0.163) |     |        |              |        |
| Blurred vision      |                 | 3.82   | [1.30; 11.23]| 0.4%   |
| Kuc, 2008           |                 | 0.64   | [0.43; 0.94] | 2.9%   |
| Alharbi, 2019       |                 | 0.95   | [0.37; 2.48] | 0.5%   |
| Mec, 2005           |                 | 1.21   | [0.44; 3.28] | 3.8%   |
| **Within group**    |                 | 1.21   | [0.44; 3.28] |        |
| (random effects model): |       |        |              |        |
| $l^2 = 79\%$, $\chi^2 = 9.54$ (p = 0.008) |     |        |              |        |
| Subgroup effect: z = 0.37 (p = 0.711) |     |        |              |        |
| **Overall**         |                 | **1.05** | **[0.98; 1.13]** | **100.0%** |
| (random effects model): |       |        |              |        |
| $l^2 = 84\%$, $\chi^2 = 66.86$ (p < 0.001) |     |        |              |        |
| Overall effect: z = 1.41 (p = 0.159) |     |        |              |        |

Figure 3. Pooled ORs of visual impairment in the smartphone overuse group compared to the less-use group.
The LOO sensitivity indicates that ORs of visual impairment in the smartphone overuse group compared to the less-use group range from 1.02 to 1.09, however none of them is statistically significant (Figure 5).

Figure 4. Baujat plot for cross-sectional studies
Figure 5. Pooled ORs of visual impairment in the smartphone overuse group compared to the less-use group from leave-one-out analysis.

**Smartphone overuse associated worse visual function scores**

The funnel plot of ES for the included controlled trial appears symmetric (Figure 6), and no statistically significant publication bias was found by Egger's test ($p = 0.066$). No statistically significant heterogeneity was present among the ESs on visual impairment incidence ($I^2 = 0\%$, $p=0.543$; Figure 7).
In all the controlled trials, the smartphone overuse group shows worse visual function scores than the less-use group, with ESs ranging from 0.40 to 0.91 (Figure 7). The pooled ES is 0.76 (95% CI: 0.53, 0.99) and statistically significant (p < 0.001), which means, compared to the
less-use group, visual function score in the smartphone overuse group is 0.76 SD worse (Figure 7).

The LOO sensitivity indicates that the results are robust, with the ESs ranging from 0.65 to 0.82, and all the ESs are statistically significant (Figure 8).

Figure 8. Pooled ESs of visual function score in the smartphone overuse group compared to the less-use group from leave-one-out analysis

**Discussion**

The purpose of this systematic review and meta-analysis was to summarize currently available evidence with reference to the relationship between smartphone overuse and visual impairment in children and young adults. Nine out of fourteen studies found a significant association between smartphone overuse and visual impairment. Our pooled results show negative but not statistically significant associations (OR = 1.05, 95% CI: 0.98, 1.13) between smartphone overuse and myopia, blurred vision, or poor vision in the included cross-sectional studies. However, the adverse effect is more apparent in children (OR = 1.06, 95% CI: 0.99, 1.14) than in young adults (OR = 0.91, 95% CI: 0.57, 1.46). We also found that smartphone overuse may cause worse visual function than less use of smartphone in the included controlled trials (ES = 0.76, 95% CI: 0.53, 0.99). As the results are mixed, further studies are warranted. To our knowledge, this is the first systematic review that comprehensively...
summarized existing data on smartphone overuse and visual impairment in children and young adults. No statistically significant association between smartphone overuse and visual impairment was found by pooling cross-sectional studies. The possible reasons might be as following.

Firstly, most of the existing studies in this systematic review were from Asia, representing the higher prevalence rates of visual impairment in these areas. However, evidence shows that the myopia prevalence in East Asia before the introduction of digital devices was already high [49]. Previous studies indicated that myopia prevalence increased more rapidly in people with more years of education and intensive schooling without particular exposure to screen devices [50-52]. For example, a study in Singapore found that myopia prevalence increased more rapidly in individuals that started elementary school after the 1980s [53]. Consistently, a study in Israel found that teenage boys who attended schools had much higher rates of myopia than students who spent less time on their books in the 1990s [49]. Therefore, education and intensive schooling may have a larger contribution to the increase in myopia prevalence. Recent studies have also extensively described the relationship between education and visual impairment [54]. Furthermore, the high prevalence of myopia from Taiwan was present in cohorts with low exposure to digital devices [52]. Thus, it is still debatable whether smartphone overuse would lead to a higher risk of myopia or other visual problems.

Secondly, most studies divided smartphone overuse as use time over 2 or 3 hours per day in our meta-analysis. However, some evidence showed that the time people spent on the digital screen was far longer [55-57], suggesting that people may use other electronic device. Other digital device overuse might also play an important role in visual impairment. Some studies have explored the relationships between digital screen time (e.g. computer, tablet, smartphone, or other handheld electronic screens) and visual impairment [56, 58-62]. For
instance, a birth cohort study (n=5074) showed that increased computer use was associated with children’s myopia development [61]. Yang et al found that screen exposure was significantly and positively associated with preschool myopia [59], which is consistent with a cohort study [62]. However, the results of impacts of screen time on visual impairment were mixed. A recent systematic review showed that screen time was not statistically significantly associated with prevalent and incident myopia [58], which may largely support our pooled result of cross-sectional studies. Thus, the relationship needs to be further validated. Moreover, given differences in various digital devices use, some studies have compared the impacts of smartphones use with other digital devices on visual impairment [20, 24, 25, 27]. The results are inconsistent. For instance, Guan et al (n = 19934) found that prolonged (>60 minutes/day) computer usage and smartphone usage were both significantly associated with greater refractive error [43]. Nevertheless, Liu et al [24] and Huang et al [25] found that myopia in children was not associated with time spent using various electronic devices including smartphone, tablet and computers. Differently, a study with a representative sample of 1884 adolescents showed that smartphone use time was associated with increased risk of visual systems, but no significant association was found for tablet use [27]. A controlled trial (n = 50) indicated that smartphone use group got higher fatigue, burning, and dryness scores than the computer use group [20]. Although the existing research supported that smartphone use might cause worse vision than other digital devices, the results need further convincing evidence to be examined due to the low number of studies.

Thirdly, several studies have shown that technology use or screen time alone are of minimal risk to visual impairment, whilst more time spent outdoors is related to reduced risk of myopia and myopic progression [25, 63, 64]. However, some researchers believe that the increased use of digital devices may lead to more near work and less time spent outdoors, resulting in a substitution effect [58, 65]. For example, Dirani et al reported that the lack of
adequate outdoor activity might be related to the rise in digital screen time [65]. To be specific, recent educational screen time might be a replacement of reading or writing, in addition to recreational screen time (e.g. computer or video games)[65]. For instance, smartphones are used by children mainly for playing games (29%) and watching videos (20%), but also for learning (19%) [66]. Thus, digital screen time might not be a causal factor, but maybe a substitute for a different type of near work. There is also some evidence that children 9 – 11 years old who spent < 2 hours playing on a computer were 1.98 times more likely to spend >1 hour outside than those reporting two or more hours of computer use [67]. Although these results might reflect a trade-off between outdoor time and digital screen time, with screen time being a proxy of indoor time, there is no evidence to confirm this substitution effect. Thus, further studies in this field are warranted.

Besides the findings in the cross-sectional studies, we also found that smartphone overuse group presented worse visual function scores than the less-use group in all the included controlled trials and the pooled result. Biologically, the effects of smartphones on ocular symptoms can be explained by two types of electromagnetic fields (EMFs); extremely low-frequency EMFs and radiofrequency (RF) electromagnetic radiation (EMR) [68, 69]. The intensity of radiation from mobile phones is relatively low with a specific absorption rate <4 W/kg [68, 70]. However, it has been reported that adverse effects, such as DNA damage and thickening of the cornea, occurs even at a specific absorption rate lower than 4 W/kg [68, 71, 72]. The local specific absorption rate has been shown higher in tissues at a younger age, suggesting higher susceptibility of adolescents to smartphones [73]. The EMFs generated by smartphones may interact with the tissues of the eyes [69, 74], which may cause apoptosis, cataract formation, edema, endothelial cell loss, inflammatory responses, and neurological effects [68, 70, 75, 76]. RF EMR may affect the body thermally and non-thermally [77], which may result in oxidative stress in the cornea and the lens [70]. These effects by EMFs
and RF EMR on the eyes, especially on the cornea and the lens, could suggest why ocular symptoms such as blurring, redness, visual disturbance, inflammation and lacrimation increased when exposed to smartphones. Although experimental studies may make causal inferences, our result needs to be further confirmed due to limited number of the existing studies.

Regarding the association between smartphone overuse and myopia examined in the cross-sectional studies, multiple ocular symptoms found in the experimental studies do not mean pathological changes in the eyes like myopia. Few longitudinal cohort studies have examined the impacts of screen exposure on myopia, but the results are inconsistent [62, 78]. To our knowledge, there are no experimental or longitudinal studies detecting the impacts of the smartphone overuse on myopia. Considering longitudinal cohort studies establishing the temporal sequence of prior exposure to environmental factors, further research may use this study design to examine whether smartphone overuse may increase the risk of developing myopia.

In addition, the heterogeneity is high in the meta-analysis of included cross-sectional studies. First of all, a large number of studies have proved potential risk factors that may result in visual impairment, which included both genetic and environmental ones [20, 26, 52, 58] (e.g. age [26], education and occupation [58], outdoor activity [20, 58] and parental myopia [20]). However, some studies did not include these variables in the multivariate analysis, which might result in inconsistent findings and might further affect the individual effect estimates and the pooled OR. Secondly, some studies only used univariate analysis to investigate the associations between smartphone use time and visual impairment [43, 65], which might hinder the exploration of their interrelationships. Thirdly, the assessment of the outcome was inconsistent. For example, some studies used a self-reported questionnaire to identify myopia [26, 27], while some other used objective assessment [24, 25]. Furthermore,
the division of smartphone overuse was inconsistent, which may preclude us from determining their significant relationships. A guideline advised limiting recreational screen time to no more than 2 hours per day [79]. Further study needs to use a broadly recognized standard to define smartphone overuse.

There are also other limitations need to be addressed. All included studies used self-reported questionnaire to evaluate smartphone use time. Participants in the included experimental studies also mostly reported their visual function using questionnaires. The questionnaires may be a potential source of error due to inaccurate reporting or recall bias of participants. Further research should adopt objective instruments to measure smartphone use time, and visual acuity (VA) screening to examine visual function. Furthermore, generalization of the results should be done with caution due to low number of studies included in each meta-analysis. Limiting the review to studies reported in English may also result in non-reporting of studies published in other languages. Nevertheless, our review has included rigorous methodological procedures to obtain and pool data from 27110 children and young adults. We also adopted a wide range of search terms to retrieve all potential articles published in English, including grey literature, which might help to reduce the publication bias in the combination.

Conclusions

Overall, current evidence suggests that the result of smartphone overuse and visual impairment in children and young adults are mixed. Although the statistically significantly negative association between smartphone overuse and visual impairment in the meta-analysis was only confirmed in controlled trials but not in cross-sectional studies, the adverse effect of smart overuse on visual functions is apparent in children. However, the relationships need to be further verified. Further research on the patterns of use, with longer follow-up on the
longitudinal associations, and the exact mechanisms behind these associations will help inform detailed guidelines for smartphone use in children and young adults. In addition, understanding the factors of smartphone overuse that account for the risk of ocular symptoms could help the growing population of smartphone users, especially children and young adults, to use smartphones in a healthier manner.

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Abbreviations:

CI: confidence interval
EMF: electromagnetic field
EMR: electromagnetic radiation
ES: effect size
JBI: Joanna Briggs Institute
LOO: leave-one-out
MeSH: Medical Subject Headings
MOOSE: Meta-analysis of Observational Studies in Epidemiology
OR: odds ratio
PRISMA: Preferred Reporting Items for Systematic Reviews and Meta-Analysis
Q: questionnaire
RF: radiofrequency
SD: standard deviation
VA: visual acuity