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Review Article

Half a century of research on Attention-Deficit/Hyperactivity Disorder: A scientometric study

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ABSTRACT

We performed a scientometric analysis of the scientific literature on ADHD to evaluate key themes and trends over the past decades, informing future lines of research. We conducted a systematic search in Web of Science Core Collection up to 15 November, 2021 for scientific publications on ADHD. We retrieved 28,381 publications. We identified four major research trends: 1) ADHD treatment, risks factors and evidence synthesis; 2) neurophysiology, neuropsychology and neuroimaging; 3) genetics; 4) comorbidity. In chronological order, identified clusters of themes included: tricyclic antidepressants, ADHD diagnosis/treatment, bipolar disorder, EEG, polymorphisms, sleep, executive functions, pharmacology, genetics, environmental risk factors, emotional dysregulation, neuroimaging, non-pharmacological interventions, default mode network, Tourette, polygenic risk score, sluggish cognitive tempo, evidence-synthesis, toxins/chemicals, psychoneuroimmunology, Covid-19, and physical exercise. In conclusion, research on ADHD over the past decades has been driven mainly by a medical model. Whereas the neurobiological correlates of ADHD are undeniable and crucial, we look forward to further research on relevant psychosocial aspects related to ADHD, such as societal pressure, the concept of neurodiversity, and stigma.

1. Introduction

With an estimated worldwide prevalence around 5–7 % in school-aged children (Polanczyk et al., 2007; Thomas et al., 2015), Attention-Deficit/Hyperactivity Disorder (ADHD) is the most common neurodevelopmental disorder (Faraone et al., 2021). Impairing symptoms of ADHD persist in adulthood in up to 60–70 % of cases (Sibley et al., 2016). ADHD is also one of the most researched disorders in child and adolescent psychiatry. By way of comparison, a simple search in PubMed on 6 June 2022 using the search terms: (child OR children OR youth* OR adolescent*) returned 10,767, 8439, 7393, and 1376 hits when these terms were matched, respectively, with "autism", "(ADHD OR Attention-Deficit/Hyperactivity Disorder OR Hyperkinetic Syndrome OR hyperkinetic disorder)", "depression", and "bipolar" (limiting the indexing of the terms in the title of the article).

Scientometrics, i.e., bibliometrics when applied to science research, allows us to summarize large amount of bibliometric data in order to present the state of knowledge and emerging trends of a research topic or field over time. To our knowledge, only three scientometric analyses of the scientific literature specifically focused on ADHD have been

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published. These previous analyses were limited in scope and in the time period considered. In the first one, López-Muñoz and colleagues (López-Muñoz et al., 2008) analyzed relevant articles on ADHD published between 1989 and 2005 and found an increase of the number of publications in the 25-year period considered, considered to be related to the introduction of medications specifically approved for ADHD. They also found the *Journal of the American Academy of Child and Adolescent Psychiatry* (*JAACAP*) and the USA to be, respectively, the scientific journal with the highest number of publications on ADHD and the country with the largest scientific productivity on ADHD. The second study (Ghanizadeh and Akhondzadeh, 2010), restricted to ADHD publications from Iran up to 2009, found that a larger number of articles were indexed in IranMedex (62 %) than in medline (38 %). The third study (Lin et al., 2021), limited to the top 100 articles on ADHD, by citations, published in the period 2014–2020, found that the most frequent topics covered by these highly cited paper related to the field of epidemiology (28 %). The two most productive countries were the USA (42 %) and the UK (13 %). Most articles were published in *JAACAP* (15 %) and *JAMA Psychiatry* (9 %).

However, whereas these previous publications provided insight on specific aspects of the ADHD literature, a more comprehensive scientometric analysis has the potential to inform the field in terms of themes that have been the focus of research in the past decades. Importantly, scientometric analyses can also reveal trends in the field, allowing us to making predictions on the future of ADHD research. This is relevant for researchers/clinicians as well as research funding bodies. Furthermore, recently, scientometric approaches have been strengthened with the inclusion of visualization and data mining techniques. These novel approaches have not yet been applied to scientometric studies on ADHD.

Therefore, we conducted a scientometric study according to state-of-the-art methods with the primary objective to evaluate how research on ADHD has evolved over the past decades in terms of research topics addressed and trends. Our secondary aims were to measure research performance and relevance in terms of countries, institutions, authors, and journals and to assess possible future topics of interest in the field based on emerging trends.

2. Methods

The study was conducted based on a pre-registered protocol (https://osf.io/cy4v2/?view_onlY = efcc2c0a379c4fb1923c3620d89e6056). The study protocol was informed by the concept of 'research weaving' proposed by Nakagawa et al. (2019), a new framework for research synthesis of both evidence and influence, accounting for their trend over time. This framework summarizes and visualizes information on a collection of papers on any given topic. Research weaving combines the power of two methods: *systematic mapping*, which provides a snapshot of the current state of knowledge, identifying areas that more research attention and those ready for full bibliometric synthesis and *bibliometrics*, which shows how pieces of evidence are connected, revealing the structure and development of a scientific field.

2.1. Search strategy and data collection

First, a comprehensive search for relevant terms in the titles, abstracts, and keywords in the *Web of Science Core Collection* (*WOSCC*) was conducted on November 15, 2021. *WOSCC* permits to retrieve references cited by published articles, and is considered the most informative database for bibliometric analyses (Mongeon and Paul-Hus, 2016). The database source was limited to the *Science Citation Index-Expanded*, with no restrictions on publication date or language. Original articles, reviews, editorials, including early access articles, were retained. The search was performed using a combination of keywords and MeSH terms related to ADHD (or equivalent definitions such as Hyperkinetic syndrome and acronyms in languages other than English e.g., TDAH in French and Spanish) and to the type of publication (e.g., "review" or "trial"). In line with previous evidence synthesis in the field of ADHD (Cortese et al., 2017), we did not include terms related to *Minimal Brain Dysfunction* or *Minimal Brain Disorder*, which would not be comparable with DSM definitions of ADHD or equivalent ICD definitions of Hyperkinetic Disorder, that were retained in our search. The full list of search terms can be found in the study protocol. To assess the quality of the reference filtering process and the homogeneity of the dataset, in line with previous studies (Moore et al., 2014), we tolerated a 5 % error by randomly subsampling 1000 references.

A detailed report of the reason for excluding articles and the extraction process is shown in the flowchart in the supplementary Fig 1.

2.2. Measures

To identify research themes and trends, we used two measures:

1) *Co-citation reference (documents) network* (commonly known as *Document Co-Citation Analysis-DCA*). Co-citation networks are formed based on co-citation relations, which connect a pair of documents concurrently cited by a third document (Small, 1973). Co-citation networks extend from a single-slide equivalent to multiple-slice network analysis, i.e., a time series of networks in order to detect critical transitions over time more effectively. The co-citation reference network reflects the intellectual base combining highly cited papers and research trends evolution, whereas co-citation networks enriched by thematic patterns of citing articles, such as the techniques used in this study, may highlight research fronts and scholarly impacts of the intellectual base. Co-citation references network allowed us also to estimate the so-called *hotspots*, i.e., *units of measure* (e.g., authors, references, countries, institutions or keywords) with significantly higher connections relative to others.
2) *Co-occurring networks of author-assigned keywords*. Co-occurrence analysis is the counting of paired data within a collection unit, here keywords. The process of constructing co-occurrence networks included identifying keywords in the text, calculating the frequencies of keywords co-occurrences, and finding clusters of keywords in the network (Hofmann and Puzicha, 1998).

Research weaving tools used in relation to co-citation reference network and co-occurring authors' keywords included *Systematic mapping*, *Intellectual structure*, *Performance analysis*, and *Collaboration networks* (Table 1). In particular, we also reported *intellectual turning point papers*", i.e., papers associated with significant contributions as a domain advance.

In relation to our secondary objectives, we estimated networks of co-author's country, networks of co-author's institutions, journal co-citation networks, co-authorship networks (accounting for the cooperation between two or more researchers, which reflects the institution and influence networks) and author co-citation analysis, which estimates the intellectual structure of a field (the state of the knowledge) based on co-citation relationships between the authors of the documents in that field (White and McCain, 1998). Author co-citation analysis assumes that pairs of authors who are frequently cited by the same documents are more likely to produce semantically related research. Research weaving tools used for the secondary objectives included *Performance Analysis* and *Collaborative (influence) network analysis* (Table 1).

2.3. Data analysis and software

We used the Bibliometrix R package (3.1.4) to analyze the publications, full references and citations of the retrieved articles, and CiteSpace (version 5.8. R3) to visualize and analyze trends and patterns in the scientific literature on ADHD. Metrics used are reported in Table 1.

Cluster labels were extracted from the keyword lists using log-

Table 1
Key concepts in scientometrics and in network analysis.

Term	Explanation
Key concepts	
Bibliometrics	It enables researchers to see how pieces of evidence are connected, revealing the structure and development of a field
Systematic mapping	It provides a snapshot of the current state of knowledge in the scientific literature, identifying areas needing more research attention and those ready for full synthesis
Intellectual structure	It refers to a set of salient attributes of the knowledge base that can provide an organized and holistic understanding of the chosen scientific domain
Performance analysis	It quantifies citation impacts and productivity using several metrics, such as publication-related metrics (total publication, number of co-authors.), citation-related metrics (total citation, average citation), and citation and publication -related metrics (g-index, number of cited papers.).
Collaboration networks	They are defined as a set of individuals who come together and collaborate on particular tasks such as publishing a paper.
Key metrics	
Betweenness centrality	The algorithm calculates unweighted shortest paths between all pairs of nodes in a graph. Each node receives a score, based on the number of shortest paths that pass through the node (Brandes, 2004; Freeman, 1977).
Burstness analysis	Citation burst is a detection of a burst event. (Kleinberg, 2003) A citation burst provides evidence that a particular publication is associated with a surge of citations. Furthermore, if a cluster contains numerous nodes with strong citation bursts, then the cluster as a whole captures an active area of research, or an emerging trend.
Modularity scores	Modularity is a measure of the structure of a graph, measuring the density of connections within a module. Graphs with a high modularity score will have many connections within a module but only few pointing outwards to other modules. Its value ranges from 0 to 1 (Newman, 2006).
Silhouette scores	Silhouette score is a metric used to calculate the goodness of a clustering technique (Rousseeuw, 1987). Its value ranges from − 1 to 1. 1: clusters are isolated from each other. 0: clusters are indifferent, or we can say that the distance between clusters is not significant. -1: clusters are assigned in the wrong way.
Sigma scores	This indicator measures the combined strength of structural and temporal properties of a node, namely, its betweenness centrality and citation burst (Chen, 2006).
Centrality divergence	The centrality divergence metric measures the structural variation caused by an article a in terms of the divergence of the distribution of betweenness centrality CB(vi) of nodes vi in the baseline network. The centrality divergence metric is potentially valuable for detecting boundary-spanning activities at interdisciplinary levels.
Modularity divergence	The modularity of a network is a measure of the overall structure of the network. Its range is between − 1 and 1. The modularity change rate of a scientific paper measures the relative structural change due to the information from the published paper with reference to a baseline network.

likelihood ratio ($P < 0.001$), and were only modified when needed following the qualitative analysis to verify the adequacy of labels.

In the networks, the frequency of occurrence is represented by the node size, and the thickness of the link between two nodes is proportional to it co-occurrence frequency. The networks timeline view also permits to clearly identify the different research trends and its evolution. The g-index, a variant of the h-index which gives more weight to highly-cited articles, was used to obtain a better measure of citation performance (Egghe, 2006).

2.4. Sensitivity analyses

To further explore the most recent research trends, we reduced the time period to the last 5 years (2016–2022), and to 2021.

3. Results

3.1. References retrieved

We retrieved 28,381 unique publications in 21 different languages (22,520 original articles, 4203 reviews, 174 editorials and 151 early access articles) cumulating 588,626 citations, from 2307 different sources (Supplementary Fig 1). The first identified paper was published in 1963 by Zrull and colleagues on the comparison of chlordiazepoxide, D-amphetamine, and placebo in the treatment of the hyperkinetic syndrome in children (Zrull et al., 1963). The number of publications gradually increased from 10 to 147 articles per year in the 1990–1997 period, then exponentially increased from 264 to 2067 articles in the 1999–2020, with an average growth rate of 11.12 % per year that continues (Supplementary Fig 2). The average citation per year grew from 2.3 in 1990–4.7 in 2020. By way of comparison with other disorders, a search in PubMed showed an increase from 541 to 6577 hits for (depression AND children) from 1990 to 2021, and from 587 to 3606 hits for (asthma AND children) in the same time period.

3.2. Analysis of co-citation reference: clusters of research and most cited papers

3.2.1. The co-cited reference network

The co-cited reference network for the 1980–2022 time period, as per CiteSpace slicing, is shown in Fig. 1. The time map of this network is also available as Fig. 2. Of note, the name of the author in black refers to the most cited author citing that cluster. For instance, the above means the psychopharmacology cluster has been cited by Ron Kessler. An alternative graphic representation of the clusters is provided in Supplementary Fig 3. This network reflects the knowledge base combining research trends evolution, frontiers and highly cited papers. Detail of each cluster can be found in Supplementary Fig 4. Clusters labels detailed are presented in Supplementary Table 1.

3.2.1.1. Clusters of research: 1980–2022 time period. We identified 31 different research clusters. Based on the largest connected component of the network, four major research trends were uncovered. We present here the clusters contributing to these trends, with cluster number ordered by the largest (#0) to the smallest (#31). As shown in Figs. 1 and 2, the first trend was on ADHD treatment, risk factors and evidence synthesis (clusters #4, #1, #2, #0, 24, #13, #11, #31 and #27), the second on neurophysiology, neuropsychology and neuroimaging (clusters #18, #7, #3, #19 and #17), the third on genetics of ADHD (clusters #6, #8, #5), and the fourth on comorbidity (cluster #9, #12, #15 and #14). Two more recent and minor recent trends on exposure to environmental toxins (clusters #29, #25 and #30) and Covid-19 (#23) were also found. The emergence of a cluster on Covid-19 might be at first surprising given that covid-19 related publications are limited to the past 2 years. However, publications on Covid-19 tend to be highly cited. For instance, Cortese et al. (2020) has been cited 163 times (28.6.22, Google scholar) despite being published only in 2020.

For the first and largest trend on ADHD treatment-risks factors-evidence synthesis, we report here the temporal evolution of the research topic clusters, with indication of the cluster silhouette score (S), size (N), mean year (Y) of co-cited articles, and most representative reference. The first research cluster,#4, concerns diagnosis/tricyclic antidepressants in the 80s, when efforts were ongoing in terms of the diagnostic definition of ADHD alongside its treatment with this type of medication class, ($S = 0.976$; $N = 339$; $Y = 1989$) (Biederman et al., 1991; Mannuzza et al., 1993) this cluster evolved into cluster #1, labeled ‘ADHD diagnosis and treatment’($S = 0.851$; $N = 409$; $Y = 1996$) which contributed to the foundation of ADHD diagnosis (Barkley, 2006) followed by cluster #2 on ‘pharmacological treatment’ of ADHD ($S = 0.875$; $N = 405$; $Y = 2006$) (Pliszka, 2007), and a relatively isolated

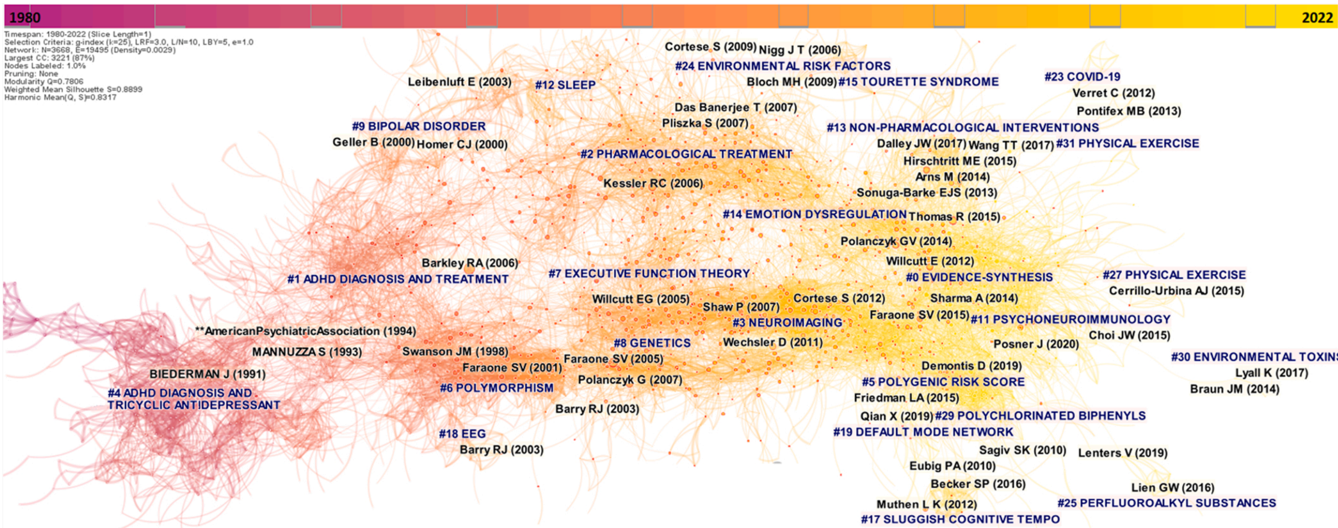

Fig. 1. Co-citation references network (1980–2022) with cluster visualization and burstness of hotspots obtained with CiteSpace. Note: Co-citation reference network with cluster visualization and burstness of hotspots. The position of the node correspond to the year of publication. The size of a node (article) is proportional to the number of times the node has been co-cited. Colored shades indicate the passage of the time, from past (purplish) to the present time (reddish). Colored tree rings refer to the nodes with high betweenness centrality (external purple tree rings) and burstness (central red tree rings). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

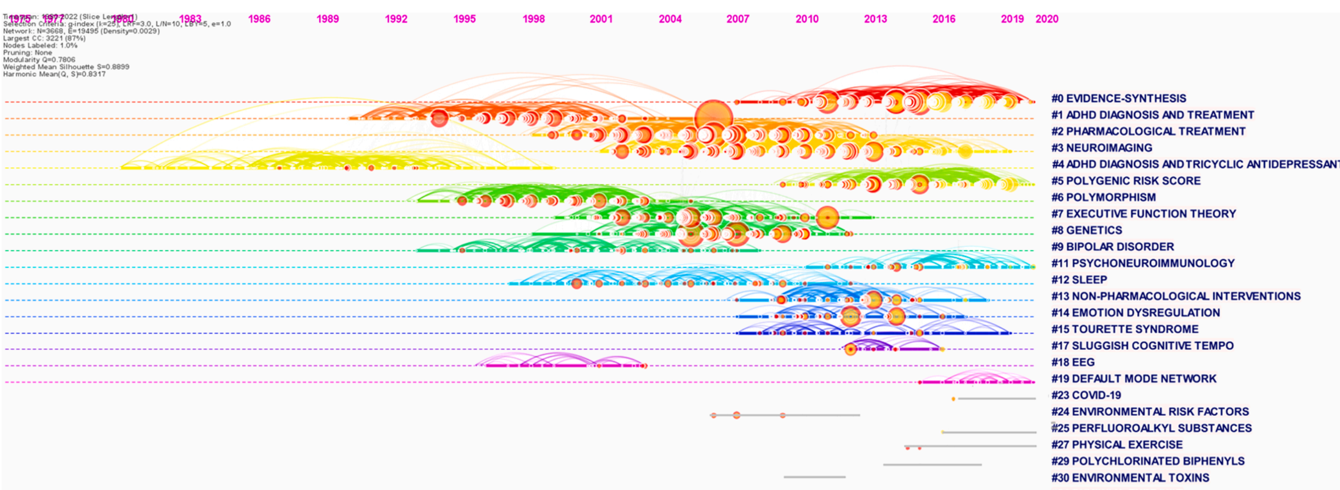

Fig. 2. Visualization of the reference co-citation network time map (1980–2022) Note: In this time map visualization, for each cluster, nodes are organized by their year of publication on horizontal lines. The 2019–2020 time frame permits to identify the latest most active co-cited clusters.

cluster #24, on 'environmental risk factors' (S = 0.999; N = 8; Y = 2008) (Banerjee et al., 2007). An important novel cluster of research has progressively appeared this last decade on 'evidence-synthesis', cluster #0 (S = 0.797; N = 434; Y = 2015) (Thomas et al., 2015), which is currently the largest cluster. This cluster present ramification with different other clusters: cluster #14 on 'emotion dysregulation'(S = 0.982; 51; 2011) (Shaw et al., 2014), and different on-going clusters: 'psychoneuroimmunology', #11(S = 0.947; 66; 2015) (Buske-Kirschbaum et al., 2013), 'nonpharmacological intervention', #13(S = 0.983; 64; 2012) (Sonuga-Barke et al., 2013), that is currently evolving into two emerging clusters (cluster #27(S = 0.999; 6; 2016), and #31(S = 1; 4; 2012) (Cerrillo-Urbina et al., 2015) on 'physical exercise', two separate clusters due to different co-citation dynamics. In general, two distinct clusters may be formed with a variety of reasons such as personal/subcommunity preferences or topic differences, but the labelling words are top-ranked words found in papers that cited these clusters. Different future developments could be particularly interesting: the two clusters will merge as a single one if more and more papers cite both of them, or two clusters can become further separated with different cluster labels.

The second major research trend concerns neurophysiology, neuropsychology and neuroimaging. This trend of research started around 1999 with a cluster on electroencephalography, #18(S = 0.997; 18; 1999) (Barry et al., 2003) it further evolved with another cluster on 'executive function theory', #7(S = 0.909; 183; 2004) (Willcutt et al., 2005), then into the largest cluster of this trend on 'neuroimaging', #3(S = 0.865; 347; 2009) (Cortese et al., 2012; Shaw et al., 2007), that developed two last clusters, one on 'sluggish cognitive tempo', #17(S = 0.995; 19; 2013) (Becker et al., 2016) and finally one on-going cluster on 'default mode network', #19(S = 0.992; 14; 2017) (Friedman and Rapoport, 2015).

The third main trend concerns genetics of ADHD. It also started around 1999, with a cluster on genetic 'polymorphism', #6(S = 0.934; 190; 1999) (Faraone et al., 2001), that continued with a cluster labeled 'genetics' on evidence-synthesis, #8(S = 0.905; 171; 2006) (Polanczyk et al., 2007) and a cluster on 'polygenic risk score'/ genome-wide association studies, #5(S = 0.845; N = 279; Y = 2015) (GDGPGC, 2013). Compared to other major trends, this trend is currently less active according to the correspondent time map, with no important *burstness* (please see Table 1 for its definition) activity these last years (Fig. 2).

The fourth trend concerns ADHD comorbidity, and starts with a cluster on 'bipolar disorders', #9(S = 0.953; 91; 2000) (Leibenluft et al., 2003). Other partially independent cluster emerges around 2004 on sleep and ADHD, #12(S = 0.988; 65; 2004) (Cortese et al., 2009), and 2012 with 'Tourette syndrome', #15(S = 0.996; 33; 2012) (Hirschtritt et al., 2015), that further evolved into the 'emotion dysregulation' cluster, #14(S = 0.982; 51; 2011) (Shaw et al., 2014). This last cluster shares important proximity with the 'evidence-synthesis', cluster #0, into which it merges.

Finally, two more recent trends appeared. One trend is on exposure to environmental toxins: 'polychlorinated biphenyls', #29 (S = 0.998; 5; 2011) (Eubig et al., 2010), 'exposure', #30(S = 0.998; 4; 2014) (Braun et al., 2014; Lyall et al., 2017), 'perfluoroalkyl substances', #25(S = 1; 7; 2018) (Lien et al., 2016); and one trend on Covid-19, #23(S = 0.996; 9; 2020) (Wang et al., 2021).

To view on-going active clusters (#0, #3, #5, #11, #19, #23, #25, and #27), we reported the time map of this network (Fig. 2), that helps to highlight the duration of a cluster and temporal positions of landmark publications. In addition, we produced a video on the link walkthrough between clusters based on burstness dynamic for co-cited reference network (1980–2022) in Supplementary Fig 5 and as a visual material on Open Science Framework.(https://osf.io/cy4v2/?view_onlY = efcc2c0a379c4fb1923c3620d89e6056).

3.2.1.2. Clusters of research: focus on 2016–2022 and 2021 period. A focus on the last 6 years of research provides a more accurate snapshot of the latest trends of research. We produced the co-citation reference network for the 2016–2022 (year slices) time period (Supplementary Fig 6, 7) and the year 2021 with monthly slices (Supplementary Fig 8, 9). The CiteSpace parameters can be found in Supplementary Information 1.

The 2016–2022 network presented four active clusters that were not highlighted in the 1980–2022 network: a cluster on 'late-onset ADHD' based on cohort studies, #7(S = 0.805; 53; 2014) (Moffitt et al., 2015) in proximity to cluster #0, a cluster on 'obesity', #4(S = 0.767; 91; 2017) (Cortese et al., 2016), in proximity to cluster #3, a cluster on 'autism spectrum disorder', #8(S = 0.813; 91; 2016) (Jensen and Steinhausen, 2015) that reactivates the 'comorbidity' trend, and a cluster on 'sport-related concussion', #15(S = 0.992; 7; 2016) (Alosco et al., 2014; McCrory et al., 2017) extending the 'physical exercise' clusters.

Furthermore, when focusing on 2021, we identified two additional recent clusters on 'functional connectivity', #2(S = 0.851; 2013) (Hoogman et al., 2017) and on 'gut microbiota', #6(S = 0.861; 82; 2015) (Sharma and Couture, 2014).

3.2.2. Turning point papers

We report the top ten cited references in Table 2. Most citations were from the largest trend on ADHD treatment, risks factors and evidence synthesis, with meta-analysis and systematic reviews. After the meta-analysis by Polanczyk and colleagues (Polanczyk et al., 2007) on the prevalence of ADHD, one of the most influential and turning point papers is the Barkley's handbook (2006) for ADHD diagnosis that is central to cluster #1. We reported in the supplement the burstness analysis (Supplementary Table 2), and conducted a structural variation analysis for the 2021 network (Supplementary Table 3). The top five papers, with the strongest modularity change rate (which measures the relative structural change due to the information from the published paper with reference to a baseline network) (Chen, 2012) were: the Faraone et al., 2021, World Federation of ADHD International Consensus Statement (Faraone et al., 2021); the Brikell and colleagues review on ADHD genetic studies (Brikell et al., 2021); the Luderer and colleague review on alcohol use disorders and ADHD (Luderer et al., 2021); the paper from the ADHD European Guidelines Group on the management of ADHD (Coghill et al., 2021); and the Zhang and colleagues study on the links between ADHD and Alzheimer disease (Zhang et al., 2021).

3.3. Network analysis of co-occurring keywords

Analysis of the most frequent keywords can inform on the trends of research and the development of research frontiers over time. We extracted the co-occurring authors' keyword network for two different time period, 1990–2022 (Supplementary Fig 10) and 2016–2022 (Fig. 3). Both networks presented a significant modularity and silhouette scores (Q = 0.3017, S = 0.6388 and Q = 0.3742, S = 0.6654 respectively). The time period starts in 1990, which is the first year with broad inclusion of search terms in published articles.

In the 1990–2022 network, six clusters were identified, labeled as follows: 'prevalence', 'response inhibition', 'ADHD', 'double blind', 'alcohol' and 'attention deficit disorder'.

In the 2016–2022 network, seven clusters were identified: 'fMRI', 'substance use', 'pregnancy', 'double blind', 'disability', 'schizophrenia', 'ADHD' and 'dopamine'. A detail of the cluster labels can be found in Table S4.

3.4. Research performance

3.4.1. Publication outputs and major journals

Two-hundred different journals were identified. The top five journals with the highest number of publications were: Journal of Attention Disorders (n = 1219), *JAACAP* (n = 840), *Journal of Child and Adolescence Psychopharmacology* (n = 638), *European Child & Adolescent Psychiatry* (n = 505), and *PLOS One* (n = 440) (Table 1 and Supplementary Fig 11). In terms of number of publications, the *Journal of Attention Disorders* ranked before *JAACAP* only in the last 5 years (Supplementary Table 5).

The co-cited journal network, which uses as unit the most co-cited journals, reveals the macro-structure of scholarly disciplines through the macro level analysis of journal titles, can be found as Supplementary Fig 12. *JAACAP* was the journal with the highest number of citations of papers on ADHD, followed by the *American Journal of Psychiatry*, *Biological Psychiatry*, *Pediatrics*, and *JAMA Psychiatry* (Table 2).

3.4.2. Co-operation network across countries and institution

The top five countries by number of articles and/or by number of citations were the USA (n = 11,768), the UK (n = 2732), Germany (n = 2303), Canada (n = 2072), and the Netherlands (n = 1789), respectively.

When focusing on the 2016–2022 period, the only difference was a progressive climb of China, presenting a clear burst in citations with a raise from the 8th to the 6th place (Table S5). The network of co-authors countries (1980–2022) is reported in Fig. 4. This network reveals important burst for China, Canada, Iran, Turkey and Brazil. In addition, the burstness analysis confirmed that China and Poland presented the latest citation burst (Table S2. A, B, C, D). We also produced the co-cited institution networks for the 2016–2022 time period. The top five institutions by number of affiliates were Harvard University (n = 1545), University of London (n = 1331), University of California (n = 1326), King's College London (n = 928) and the Massachusetts General Hospital (n = 874). The University of California Irvine, New York University, and the National Institute of Mental Health were the most influent institutions (Supplementary Table 5). The top five most cited institutions for last five years (2016–2022) were King's College London,

Table 2
The top 10 most cited journals and references.

Top 10 journals of our author's journal co-cited network

Journals with most articles	Initial year	Impact factor (2019–2020)	Total articles (%)	Total articles	Journal H-index	Journals with most citations	**Total citations**
1. Journal of Attention Disorders	1996	3.25	4.51	1219	72	1. Journal of the American Academy of Child and Adolescent Psychiatry	8165
2. Journal of the American Academy of Child and Adolescent Psychiatry	1987	8.82	3.10	840	243	2. American Journal of Psychiatry	7544
3. Journal of Child & Adolescent Psychopharmacology	1994	2.57	2.36	638	84	3. Biological Psychiatry	6360
4. European Child & Adolescent Psychiatry	1992	3.92	1.86	505	93	4. Pediatrics	6218
5. PLOS ONE	2006	3.24	1.62	440	332	5. JAMA Psychiatry	6016
6. Biological Psychiatry	1969	13.38	1.45	392	319	6. Journal of Child Psychology and Psychiatry	5481
7. Journal of Child Psychology and Psychiatry	1960	6.47	1.43	387	211	7. The Journal of Clinical Psychiatry	3909
8. Psychiatry Research	1979	4.79	1.30	354	134	8. Journal of Attention Disorders	3820
9. Pediatrics	1948	7.12	1.23	334	345	9. The Lancet	3633
10. American Journal of Medical Genetics (part B)	1995	3.56	1.06	288	126	10. Psychological Medicine	3415

Top 10 co-cited references of our reference co-cited network

Number of citations in the network	Number of citations in the literature[a]	Year	Source	Vol	Pages	Title	Doi	Type of paper	Related cluster in Fig. 1
382	6233	2007	Am J Psychiatry	164	942–8	Polanczyk G, de Lima MS, Horta BL, Biederman J, Rohde LA. The worldwide prevalence of ADHD: a systematic review and metaregression analysis.	⟨https://doi.org/10.1176/ajp.2007.164.6.942⟩	Meta-analysis	7, 3, 24
367	1927	2006	Guilford Press	–	–	Barkley RA. Attention-deficit hyperactivity disorder: A handbook for diagnosis and treatment, 3rd ed.	⟨https://doi.org/10.1177/1087054707305334⟩	Diagnosis Handbook	1, 18
349	1299	2015	Pediatrics	135	994–1001	Thomas R, Sanders S, Doust J, Beller E, Glasziou P. Prevalence of attention-deficit/hyperactivity disorder: a systematic review and meta-analysis.	⟨https://doi.org/10.1542/peds.2014-3482⟩	Meta-analysis	0, 11
346	4291	2006	Am J Psychiatry	163	716–23	Kessler RC, Adler L, Barkley R, Biederman J, Conners CK, Demler O, Faraone SV, Greenhill LL, Howes MJ, Secnik K, Spencer T, Ustun TB, Walters EE, Zaslavsky AM. The prevalence and correlates of adult ADHD in the United States: results from the National Comorbidity Survey Replication.	⟨https://doi.org/10.1176/ajp.2006.163.4.716⟩	Comparative study	2, 24
346	3133	2005	Biol Psychiatry	57	1313–23	Faraone SV, Perlis RH, Doyle AE, Smoller JW, Goralnick JJ, Holmgren MA, Sklar P. Molecular genetics of attention-deficit/hyperactivity disorder.	⟨https://doi.org/10.1016/j.biopsych.2004.11.024⟩	Literature review	8
278	1393	2014	Int J Epidemiol	43	434–42	Polanczyk GV, Willcutt EG, Salum GA, Kieling C, Rohde LA. ADHD prevalence estimates across three decades: an updated systematic review and meta-regression analysis.	⟨https://doi.org/10.1093/ije/dyt261⟩	Systematic review/ meta-regression	0
270	651	2015	Nat Rev Dis Primers	1	–	Faraone SV, Asherson P, Banaschewski T, Biederman J, Buitelaar JK, Ramos-Quiroga JA, Rohde LA, Sonuga-Barke EJ, Tannock R, Franke B. Attention-deficit/hyperactivity disorder.	⟨https://doi.org/10.1038/nrdp.2015.20⟩	Literature review	0, 5, 11
262	1929	2012	Neurotherapeutics	9	490–9	Willcutt EG. The prevalence of DSM-IV attention-deficit/hyperactivity disorder: a meta-analytic review.	⟨https://doi.org/10.1007/s1331101201358⟩	Meta-analysis	0
260	1245	2014	J Am Acad Child Adolesc Psychiatry	53	34–46	Visser SN, Danielson ML, Bitsko RH, Holbrook JR, Kogan MD, Ghandour RM, Perou R, Blumberg SJ. Trends in the parent-report of health care provider-diagnosed and medicated attention-deficit/hyperactivity disorder: United States, 2003–2011.	⟨https://doi.org/10.1016/j.jaac.2013.09.001⟩	Systematic review	0
257	1201	2005	Lancet	366	237–48	Biederman J, Faraone SV. Attention-deficit hyperactivity disorder.	⟨https://doi.org/10.1016/S0140-6736(05)66915-2⟩	Literature review	0, 13

[a] Number of citations in the literature according to the journal where the paper was published.

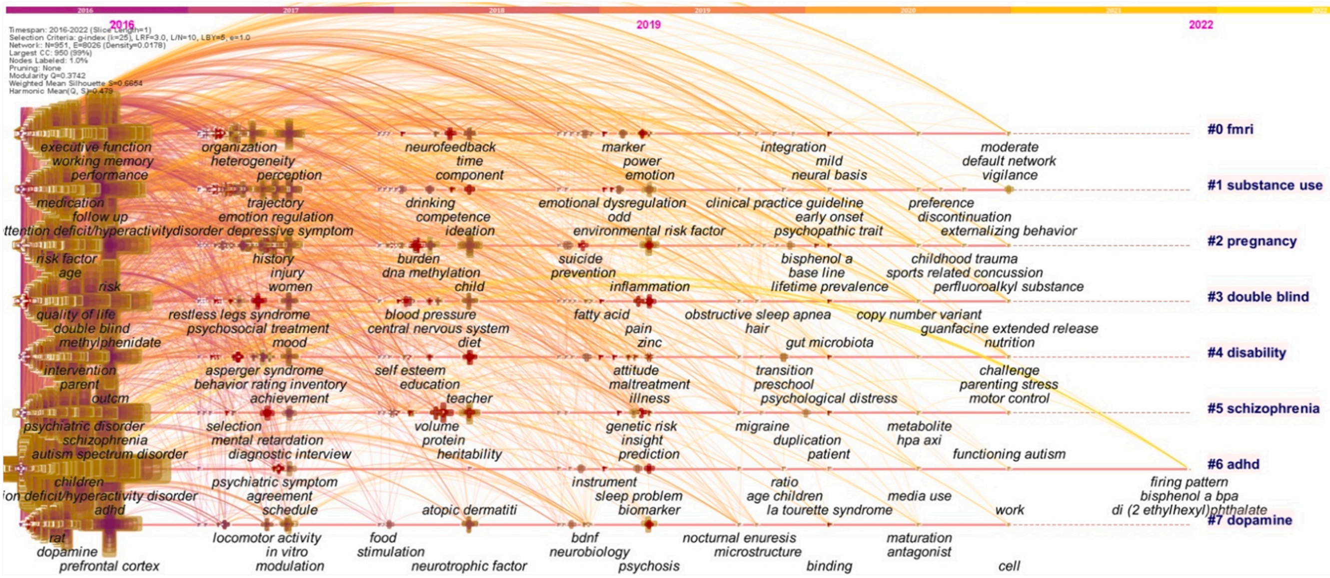

Fig. 3. Timeline visualization of co-occurring authors keywords network (2016–2022). Note: In this co-occurrence author's keywords analysis, the size of the cross are proportional to the frequency of keyword occurrence.

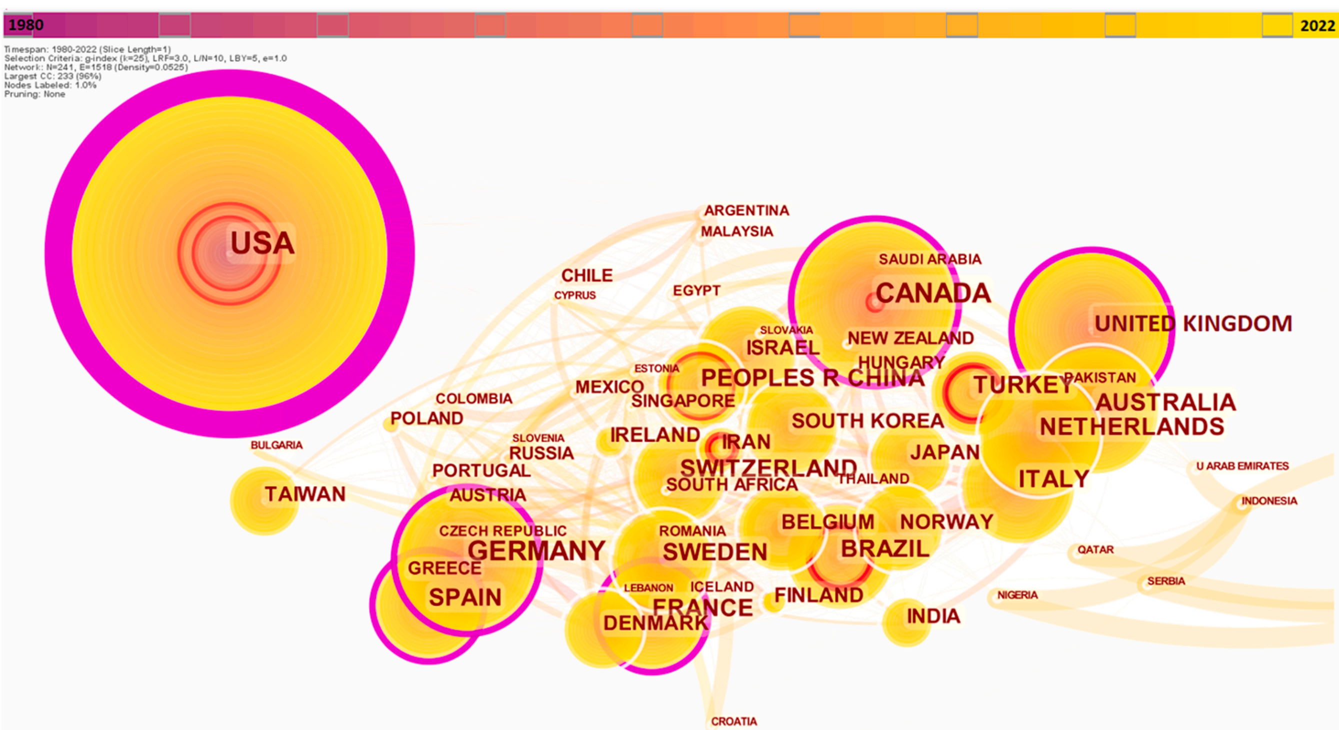

Fig. 4. Network of co-authors' countries (1980–2022) Note: The network of co-authors countries permits to reveal the collaborative country network. Betweenness centrality organize the network, with the countries presenting the most important centrality being at the center of the network. The position of the node corresponds to the mean year of publication. The outermost purple ring denotes the centrality level, and highly central nodes are considered pivotal points in the research field. We limited the nodes to the 60 first countries.

Karolinska Institute, Harvard Medical School, Radboud University Nijmegen, and University of Toronto, and the institutions with the strongest strength of citation burst were the University of Paris, Nanjing Medical University, Stockholm Health Care Services and, the Central South University and University of Duisburg-Essen (Supplementary Table 2 E, F). Clusters of research collaboration revealed the relative paucity of cooperation of the Turkish research network (Supplementary Fig 13). Finally, the analysis of co-authorship network can be found in Supplementary Fig 14 and Supplementary Table 6.

4. Discussion

4.1. Identification of trends and future of evidence synthesis

To our knowledge, this study is the most comprehensive and detailed scientometric analysis of the ADHD scientific literature. Scientometric analysis propose a reproductive snapshot of the current state of knowledge and highlights how evidence is connected, revealing the structure and development of research on ADHD. Of note, some domains for which there may be a large body of publications might have not been highlighted in our analysis if the related papers did not receive a high number of publications.

After initial descriptions of children with features reminiscent of ADHD (e.g., a mischievous and uncontrollable ten-year-old boy by Haslam in Scotland – 1809 (Taylor, 2011), the German "fidgety Phil" by Hoffman in 1845 (Taylor, 2011), or the *touch*-à-*tout* ("touching everything") boy by the French author Moreau - 1888) (Konofal, 2019), the first "scientific" account of an equivalent of ADHD is often considered to be the one by George Frederick Still (the founder of pediatrics in England, who described a syndrome phenomenologically similar to ADHD, that he labelled as a "deficit of moral control"), even though the focus of his work was on defects of moral control rather than inattention/hyperactivity/impulsivity (Taylor, 2011). Afterwards, "modern" research on ADHD took off in the 70s. Since then, ADHD has evolved as a complex and in part controversial entity, despite a large body of evidence, providing compelling answers to a series of questions on the disorder (Faraone et al., 2021).

The inspection of our co-citation reference network shows that in the early phases of the "modern" literature, publications on ADHD were mainly focused on its diagnosis and pharmacological treatment. In fact, our first cluster, in chronological order, grouped citations on tricyclic antidepressants (alongside those on diagnosis) that were tested in the 80s as a possible treatment for ADHD, a long time after the report, by Bradley in 1937, of positive effects of benzedrine sulfate, an amphetamine compound, on ADHD symptoms (Strohl, 2011). Whereas there is currently meta-analytic evidence that tricyclic antidepressants are efficacious for ADHD symptoms (Otasowie et al., 2014), at least in the short term, such evidence is limited to a small number of RCTs (n = 5, desipramine) and tricyclic antidepressants are not recommended in current clinical guidelines for ADHD due to concerns around their possible cardiovascular effects. Following these first lines of research, research on ADHD addressed then its neurophysiological correlates (initially with EGG given its availability across labs), genetics underpinnings (prompted by findings of high heritability - around 70 %) (Faraone and Larsson, 2019), and relevant comorbidities/differential diagnoses, such as sleep disorders and bipolar disorder. Comorbidities evolved later on into other areas, such as Tourette, reinforcing the notion of ADHD as a neurodevelopmental disorder that was made official in the DSM-5. Subsequently, an increasing focus, starting around 2010, has been on the dimensional constructs such as the role of emotional dysregulation that, even if not currently conceptualized as a core feature of ADHD, many in the field deem an essential characteristic of individuals with ADHD, especially in adulthood (Lenzi et al., 2018; Shaw et al., 2014). Furthermore, a large body of literature has focused on executive dysfunctions, that have been conceptualised, for a while, to underlie ADHD (Barkley, 1997). However, it is currently well established that the profile of executive dysfunctions is heterogeneous across individuals with ADHD and some of them may present with no executive dysfunction at all (Lambek et al., 2018). More recently, a sizeable portion of the neuropsychological literature has focused on the concept of *sluggish cognitive tempo*, characterized by excessive daydreaming and slow processing of information, which nosographic links with ADHD remain unclear and are an active area of investigation (Becker, 2021). The availability of neuroimaging approaches such as magnetic resonance imaging has fuelled another important line of research in ADHD starting in the 90s, initially focused on the structural and then on the functional brain correlates. More recently, neuroimaging studies on ADHD have addressed the role of the default-mode-network (DMN) following the implementation of resting state MRI methods (Cortese et al., 2021), and the proposal of the DMN hypothesis of ADHD, i.e., that attentional lapses are causes by inappropriate activity of the DMN during task-based activities (Sonuga-Barke and Castellanos, 2007). Likewise, genetic research has evolved including more advanced approaches, such as polygenic risk scores. The past two decades have seen also an increasing interest on non-pharmacological approaches for ADHD, possibly due to concerns around side effects of medication and the lack of solid evidence on their long-term effects (Cortese, 2019). Of note, current evidence shows that the role of non-pharmacological approaches for ADHD core symptoms, when considering blind raters of symptoms, is unclear (Coghill et al., 2021). A conceptually related more novel cluster of publications relates to the role of physical exercise as possible intervention for ADHD, even if to date its actual impact in decreasing ADHD core symptoms severity remains uncertain (Montalva-Valenzuela et al., 2022). In the past two decades, the large body of publications on ADHD has fostered the publication of meta-analyses that now form a highly cited body of research in the field and have contributed to inform clinical guidelines (Cortese, 2020), as well as provided important figures on the epidemiology of ADHD by pooling data from studies across the world (Polanczyk et al., 2007).

Complementing genetic research, more recent investigation has been devoted to environmental risk factors, mainly biological ones. In particular, there has been a focus on toxins/chemicals. Given a number of methodological issues in currently available studies, the role of chemicals, in particular pesticides, in the pathophysiology of ADHD needs to be further elucidated (Tessari et al., 2022).

When zooming more closely on the past five years, interesting clusters emerged, including lines of research on: 1) the relationship between ADHD and autism, likely strengthened by the removal, by the DSM-5, of the veto of co-diagnosing AHD and autism; 2) the link between ADHD and obesity, reflecting the awareness of significant links between mental and physical conditions (Cortese et al., 2020); 3) gut-microbiome, in line with a recent research trend across several areas in psychiatry (Cryan and de Wit, 2019); 4) a controversial topic, i.e., the possible adult onset of ADHD, which some researchers posit is accounted for by a late manifestation symptoms that were present in childhood but were not impairing due to effective scaffolding (Riglin et al., 2022).

Overall, our scientometric analysis shows that the bulk of the scientific literature on ADHD over the past decades has been driven by a medical model, addressing the neurobiological correlates of the disorder. Arguably, this has been influenced by initial neurological formulations of what can be considered as precursors of ADHD, namely minimal brain damage (Taylor, 2018). More distally in time, the notion of constitutional *deficit* resonates with the idea, put forward after the industrial revolution, that children were not merely "economic units" for the family (workers) but human beings characterized by a developmental process that could go awry (Taylor, 2018).

Whereas the neurobiological bases of ADHD are undeniable, and are supported by a large body of evidence (Faraone et al., 2021), we think, in line with Hinshaw and Scheffler (Hinshaw and Scheffler, 2018), that researchers in the field should avoid reductionist models of ADHD, and focus on the role of cultural/contextual factors, alongside neurobiological factors. Hinshaw and Scheffler (Hinshaw and Scheffler, 2018) posit that pressure for performance and productivity are key elicitors and "revealers" of ADHD symptoms that have an undeniable neurobiological basis, making ADHD at once a biological and cultural phenomenon. We look forward to seeing more research in this area. Relatedly, other psychosocial topics of interest are stigma (only 20 hits, from a PubMed search on 6 June 2022 matching terms for ADHD and stigma in the title of the publication) and neurodiversity (only 1 hit), for which no large clusters were detected.

4.2. Research networks

The secondary objective of this study was to assess research performance from institutions, countries, and authors. We have provided a large amount of data that we deem will be helpful for the readers, particularly those involved in research. While a detailed appraisal of these data goes beyond the scope of this paper, we highlight here one relevant finding. In contrast with the -hopefully now outdated-misconception that ADHD is an "American condition", it is interesting to note that, while the USA ranked first in terms of number of articles and/

or by number of citations, the two most cited institutions in the past five years were King's College London and Karolinska Institute (Sweden), and important bursts were found for China, Canada, Iran, Turkey and Brazil. In line with Cortese and Coghill (2018), we look forward to seeing more research from less advantaged countries, to gain insight on the interplay between neurobiological and socio-cultural factors in ADHD.

4.3. Limitations

Our findings should be considered in the light of some limitations. First, scientometric studies rely mostly on co-citations. This can be problematic in particular with 'citation distortion', i.e., distortions in the persuasive use of citations, that can be used to establish unfounded scientific claims as fact (Greenberg, 2009). Such bias can however be detected with a detailed examination of hotspots. Second, we only searched WOSCC, which can limit the type of retrieved publication (Singh et al., 2021; Visser et al., 2021). For most databases, such as PubMed or Embase, full references text and citations lists are not available. The actual differences in references classifications between WOSCC and other sources such as Scopus may pose non-trivial challenges for merging references from different databases, which may require a significant degree of manual interventions. The future development of software could make it possible to simultaneously analyse results from different databases with reliable automatic duplicate removal. A third limitation concerns the influence network, as our co-citation network is only based on first authors, which does not adequately reflect the authors' influence. Co-occurrence networks are also affected by the keyword different expressions, which can affect clustering. Fourth, we could not cover all publications on ADHD. We excluded article format other than Original articles, reviews, editorials and, notably, Web of Science is more selective, compared to other databases (e.g., PubMed) in terms of inclusion of scientific journals. Finally, the most recent trends of research can be difficult to detect, considering that many recent publications are not sufficiently cited. Indeed, publications and subsequent citations have a lag. However, cluster labels were drawn from citing articles to the publications. We did not only consider the citation counts, but also took into account who made the citations in what context, which significantly reduces the lag because a citing article can be just published.

5. Conclusions

Research on ADHD over the past decades has been driven mainly by a medical model. Whereas the neurobiological correlates of ADHD are undeniable and crucial, we look forward to further research on relevant psychosocial aspects related to ADHD, such as societal pressure, the concept of neurodiversity, and stigma. Overall, our conclusions are in line with the need to transcend the reductionism that is often applied to the concept of ADHD, as highlighted by Hinshaw who pointed to the exclusive/prevalent use of a biological model of the condition at the expense of other complementary models (Hinshaw and Scheffler, 2014). We hope that the present scientometric study will increase awareness of ADHD research trend over time and its future directions among clinicians and researchers in the field, and inform funding bodies about research priorities in ADHD. In the future, it will be of interest to also systematically assess the different factors that drive and influence the conceptualisation of ADHD, and those that determine possible conceptual shifts.

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Data Availability

Data will be made available on request.

Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.neubiorev.2022.104769.

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