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RESEARCH

Effect of age and driving experience on road sign comprehension: a systematic review and meta-analysis of two decades

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Abstract

Road sign comprehension is integral to safe driving, with age and driving experience influencing individuals' ability to interpret signs effectively. This study conducted a systematic review and meta-analysis to synthesise research data from 2004 to 2024 to understand how age and driving experience affect the ability to comprehend road signs. The review identified factors influencing comprehension, including personal characteristics and cognitive design features. Meta-analyses revealed significant differences in accident rates between young and older drivers and novice and experienced drivers. Specifically, the analysis of 3,330 participants (1,746 young drivers and 1,584 older drivers) showed that young drivers were involved in 15.88% points more accidents than older drivers, with high heterogeneity across studies (I^2 = 99%, $P<0.00001$). Similarly, among 1,958 participants (721 novice drivers and 1,237 experienced drivers), novice drivers were involved in 8.68% points more accidents than experienced drivers, also with substantial variability (I^2 = 98%, $P<0.00001$). The review proposed future research directions to improve road sign design, enhance drivers' understanding, and promote road safety, emphasising the importance of advanced cognitive design features and contextual signage solutions. Insights for policymakers, transportation authorities, and researchers were highlighted, stressing the need to assess traffic sign comprehension and to regularly incorporate user-centred design approaches. Sensitivity analyses and publication bias assessment further strengthened the review's findings, laying the groundwork for evidence-based interventions to enhance road safety worldwide.

Keywords Age · Driving experience · Future directions · Road sign comprehension

Introduction

Road signs convey essential information to drivers, including speed limits, directions, warnings, and regulatory instructions (Yadav & Velaga, 2021; Mustapha et al., 2024). However, several factors can influence a driver's ability to interpret and respond to these signs effectively (Sahu et al., 2024). Age-related changes in cognitive skills, such as processing speed, attention, and visual perception, may impair older drivers' ability to comprehend road signs accurately (Schulz et al., 2020). Similarly, driving experience, encompassing both years of driving and exposure to diverse traffic environments, can also shape an individual's proficiency in interpreting road signs (Mutu & Yakar, 2022).

The multifaceted nature of road sign comprehension underscores the intricate interplay between individual characteristics and environmental factors. Some studies suggest that older drivers may have difficulty comprehending complex road signs compared to younger drivers (Falkenstein et al., 2020), whereas others argue that driving experience may mitigate these age-related effects (Abd Rahman et al., 2020; Ucińska et al., 2021). Despite the wealth of research dedicated to exploring these relationships, findings have been inconsistent, necessitating a comprehensive synthesis of existing evidence to clarify how age and driving experience influence road sign comprehension.

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Even with advancements in traffic sign design and road safety programmes, road traffic accidents remain a significant global public health issue. One contributing factor to these accidents is the misinterpretation or failure to notice road signs, particularly among older drivers who may experience age-related cognitive decline (Touliou et al., 2019). According to traffic safety data, misinterpretation or failure to recognise road signs contributes to approximately 20% of road traffic accidents globally, with older drivers disproportionately represented in these statistics (Fausto et al., 2021; Gade et al., 2023). Studies in the European Union report that nearly 25–50% of crashes involving older drivers are linked to failure to comply with traffic signs (Fisa et al., 2022; Zhao & Yamamoto, 2021). Furthermore, Burghardt and Pashkevich (2020) indicated that drivers over 65 have a 1.5 times higher likelihood of being involved in intersection-related crashes, often associated with misreading or ignoring road signs. Understanding how age and driving experience influence road sign comprehension is essential for developing targeted interventions to improve road safety and mitigate the risks associated with an ageing population.

Despite decades of empirical research on driving performance, a comprehensive synthesis of the combined effects of age and driving experience on road sign comprehension remains absent in our understanding. Road sign comprehension is a critical component of safe driving. Yet, global evidence on how cognitive ageing and experiential factors influence this ability has not been systematically integrated. The existing body of literature has produced inconsistent findings, with some studies documenting significant age-related declines in sign comprehension (Abduljabbar et al., 2020; Mustapha et al., 2022a; Schulz et al., 2020), and others suggesting that accumulated driving experience may compensate for these declines (Liang et al., 2020; Ucińska et al., 2021; Xiang et al., 2021). These inconsistencies point to a fragmented understanding of how age and experience interact to shape drivers' processing of traffic signage.

Although several studies have explored the independent effects of age and driving experience (Allen et al., 2019; Barrett & Gumber, 2019), direct comparisons of their relative contributions remain scarce. Additionally, much of the existing research is limited in scope, often focusing on specific age cohorts or localised populations, thereby constraining the generalizability of its findings. These limitations hinder the development of targeted interventions and policy strategies to support driver safety across age groups.

A critical research gap exists in understanding the combined and interactive effects of age and driving experience on road sign comprehension. Although, prior studies have examined these factors independently, there has been no systematic synthesis of how they jointly influence comprehension across diverse populations. The present systematic review and meta-analysis aim to address these gaps by synthesising 20 years (2004–2024) of empirical evidence across diverse contexts. Previous research has investigated age or driving experience in isolation; however, few studies have synthesised their combined effect on road sign comprehension using a meta-analytic approach. This study addresses that gap by integrating two decades of global evidence to quantify how these variables interact. Integrating the findings across a broad range of study populations and methodologies, this study quantifies the individual and interactive effects of age and driving experience on road sign comprehension. The resulting analysis offers a more comprehensive understanding of the cognitive and experiential factors influencing drivers' ability to recognise and interpret road signs, providing a foundation for evidence-based improvements in signage design, driver education, and transportation policy.

Objectives

The main goal of this review is to evaluate how age and driving experience affect the ability to read traffic signals. Synthesising data from studies across various locations and contexts, the review identifies patterns and factors contributing to variations in road sign comprehension among demographic groups. The specific objectives are to:

1. Determine the extent to which age affects road sign comprehension.
2. Examine the impact of driving experience on road sign comprehension.
3. Assess how the interaction between age and driving experience influences drivers' ability to interpret road signs across populations.

In addition to addressing these objectives, the study also highlights gaps in current knowledge, proposes directions for future research, and offers actionable insights for policymakers and transport authorities.

Scope

This study conducted a systematic review and meta-analysis to investigate the effects of age and driving experience on traffic sign comprehension. The focus was on studies completed from 2004 to 2024. The review seeks to offer a current and thorough examination of research discoveries in this field by focusing specifically on this period.

Literature review

Road traffic signs are essential elements of transport systems, designed to convey critical information that ensures safe and efficient road use. Accurate comprehension of these signs enables drivers to make timely and appropriate decisions, reducing the risk of accidents. Despite the existence of international standards such as the International Organisation for Standardisation (ISO) 3846 and the American National Standards Institute (ANSI) Z535.3, which promote the consistency, clarity, and effectiveness of signage, evidence suggests that drivers often struggle to interpret signs correctly (Mustapha et al., 2024). This disconnect between standardisation and real-world comprehension underscores the importance of examining the human factors influencing sign interpretation.

Numerous studies have investigated how age, driving experience, education, and contextual factors affect the ability to understand road signs. A general trend in the literature shows that sign comprehension tends to decline with age, likely due to age-related changes in cognitive function, including slower information processing and reduced working memory. However, several findings suggest that experienced drivers, particularly those with many years of practice or professional roles, can somewhat compensate for these declines (Ben-Bassat & Shinar, 2015; Shoaib et al., 2020; Singh & Kathuria, 2023). These findings indicate a complex relationship between ageing and driving experience and highlight the importance of examining how these factors interact. This is further supported by Hilt and Cardellicchio (2020), who found that age-related decline in visual attention among older drivers significantly impaired road sign recognition, even among those with ongoing professional driving activity.

Drivers with greater exposure to the road environment tend to demonstrate better sign recognition and interpretation. Experience enhances familiarity with visual cues and strengthens the ability to make sense of symbolic and text-based information. Educational background also plays a key role in sign comprehension, with higher levels of education linked to improved performance. This may be attributed to enhanced cognitive and literacy skills that support understanding complex or abstract visual messages. For example, Mustapha et al. (2025) found that individuals with higher levels of education performed significantly better on road sign recognition tasks, especially for signs involving greater symbolic complexity or lower semantic transparency. However, increased awareness does not always lead to safer driving behaviour (Abu Abdo & Al-Ibrahim, 2016; Sullivan & Nieuwenhuys, 2022). This indicates the need for both education and enforcement to improve road safety.

Contextual factors further shape comprehension outcomes. Studies conducted in diverse settings, including Nigeria (Mustapha et al., 2023), Jordan (Obeidat et al., 2022), Pakistan (Farooq et al., 2020), the Philippines (Brucal et al., 2015), and Thailand (Kongcharoen et al., 2022), highlight the role of culture, language, and local design conventions in how signs are interpreted. Tourist populations, for instance, often show lower comprehension of symbolic signs, favouring text-based alternatives due to unfamiliarity with the local context (Choocharukul & Sriroongvikrai, 2017). Similarly, Mustapha et al. (2024) observed that foreign drivers in Germany, especially those unfamiliar with European signage conventions, exhibited slower response times and lower comprehension accuracy when interpreting symbolic road signs. Such findings suggest that effective signage must account for universal design principles and local user characteristics.

Cognitive design features refer to aspects like semantic distance, complexity, and familiarity of the symbol. Travel characteristics include driving frequency, mode of transport, and road familiarity. These elements strongly influence the ease and speed with which drivers process sign information. Despite this, relatively few studies have systematically examined how modifications to these features could improve comprehension across different user groups.

A significant gap in the literature lies in the lack of intervention-focused research. Many studies identify low comprehension levels but do not test potential solutions such as redesigns, driver training, or awareness campaigns. Additionally, the focus of many investigations is limited to urban or region-specific populations, making it difficult to generalise findings across broader national or international contexts.

The lack of synthesis across existing studies presents a challenge for researchers and policymakers seeking evidence-based solutions to improve road sign comprehension. Although numerous factors have been identified, there is limited clarity about the relative contributions of age and experience, or about how they interact across settings.

This review addresses that gap through a systematic review and meta-analysis of two decades of research on road sign comprehension. The objective is to clarify how age and driving experience influence sign interpretation, identify consistent patterns and contradictions in the literature, and guide future research and policy development. A clearer understanding of these relationships can inform the design of more inclusive road signage and

support targeted interventions to enhance driver comprehension and reduce accidents.

Methodology

Search strategy

A systematic search of two databases (Google Scholar and ScienceDirect) for papers published from 2004 to 2024 was conducted to identify pertinent studies examining the relationship between age, driving experience, and road sign comprehension, using the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guideline. The search strategy entails three steps: (1) Relevant keywords and phrases related to road sign comprehension were identified. (2) A combination of keywords and phrases using Boolean operators was used to construct search queries. The search term using Boolean operation is ((Comprehension OR understanding) AND future directions AND influential factors AND (road sign OR traffic sign)). (3) Search results were screened based on title, abstract, and keywords to identify potentially relevant studies.

Inclusion and exclusion criteria

The inclusion criteria for this systematic review and meta-analysis encompass studies that evaluate road sign comprehension in licensed adult drivers aged 18 and above. Selected studies must be published in peer-reviewed journals and conference proceedings, made available in English, and published between 2004 and 2024. Studies should examine the relationship between age and/or driving experience and road sign comprehension and provide quantitative data sufficient to calculate effect sizes (for example, means, standard deviations, correlation coefficients). Validated measures of road sign comprehension must be used, and only studies with full-text availability were included. Exclusion criteria comprised studies on off-road sign comprehension or analogous contexts, qualitative studies, theoretical or conceptual papers, editorials, and those lacking statistical data or methodological clarity necessary for aggregation. Additionally, grey literature sources such as reports, books, book chapters, theses, dissertations, and protocols were excluded, along with studies not available in English.

Study selection process

Two trained independent reviewers examined the titles, abstracts, and full texts of studies to identify publications that potentially met the inclusion criteria, using Rayyan. Rayyan is an avenue for collaborative intellectual survey of systematic and literature reviews (Ouzzani et al., 2016). The study selection process comprised four stages: First, an initial screening of search results was conducted based on keywords, titles, and abstracts to identify potentially relevant studies. Subsequently, selected studies underwent a full-text assessment to determine eligibility, guided by predefined inclusion and exclusion criteria. Following these studies, participants fulfilling the inclusion criteria were selected for data extraction and synthesis. Finally, any differences that arose during the selection process were resolved through discussion and consensus among the reviewers, ensuring consistency and accuracy in the selection process. Figure 1 displays the flow chart of the selection procedure.

Data extraction and synthesis methods

The same approach, with two trained reviewers, was employed for data extraction and quality analysis, as well as for record-keeping of study characteristics. A standardised, pre-piloted form was used to extract data from the included

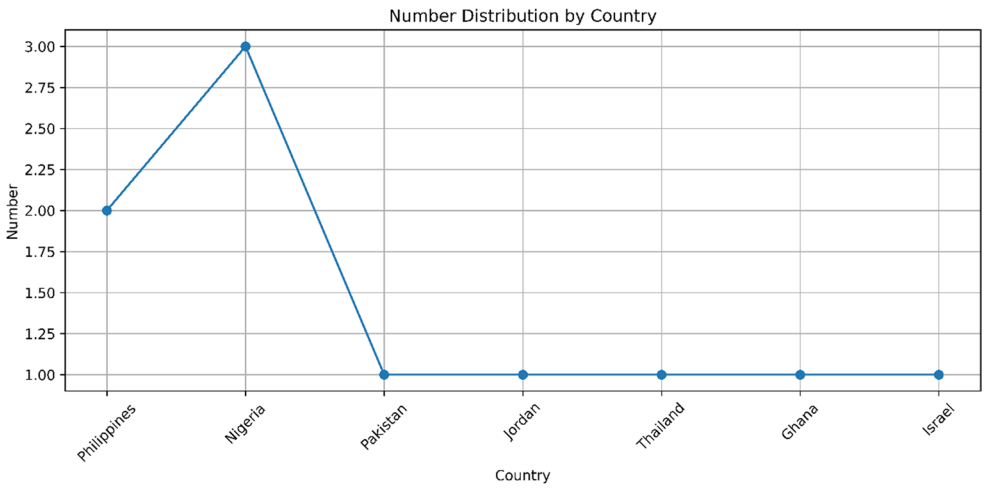

Fig. 1 Countries based on the number of articles

studies to assess research quality and evidence synthesis. The data extraction and synthesis method includes several essential steps: initially, an exhaustive data extraction form was established to systematically obtain the appropriate data from selected studies that involve study characteristics (such as author, publication year, and study design), sample characteristics (including demographics, population, and sample size), and findings. Afterwards, data from the chosen studies were retrieved by one reviewer and thoroughly reviewed by a second reviewer to guarantee accuracy and completeness. The extracted data was then synthesised to identify patterns, trends, and common themes in road sign comprehension. Lastly, the findings were presented through narrative synthesis, supplemented by quantitative analyses, such as meta-analysis, where applicable and feasible, given sufficient data availability.

Risk of bias assessment

A pair of reviewers independently evaluated the risk of bias in the included studies. This instrument comprises seven items relating to internal and external validity and statistical information necessary for the interpretation of data. One point was granted for each completed criterion (maximum 7 points), and conflicts were addressed through debate and with the cooperation of a third reviewer.

Statistical analyses

The analyses were conducted using Review Manager (RevMan, Version 5.4). Studies reporting comparable outcome measures were pooled using random-effects meta-analyses to account for anticipated heterogeneity. Mean differences for continuous outcomes related to age and driving experience were estimated, along with 95% confidence intervals (CIs) and two-sided p-values.

A random-effects model with inverse variance weighting was used to generate pooled effect estimates. A descriptive analysis was undertaken, where the quality of included studies did not support statistical aggregation. Heterogeneity across studies was assessed using the I^2 statistic, which quantifies the proportion of variance due to heterogeneity rather than chance. I^2 values of 25%, 50%, and 75% indicated low, moderate, and high heterogeneity, respectively, with $p < 0.05$ considered significant.

Pre-planned and post hoc subgroup analyses were conducted to explore potential differences in effect estimates related to age groups (young vs. old) and driving experience levels (novice vs. experienced). “Young” drivers were defined as those aged 16–35, and “older” drivers as those aged 60 and above. Drivers aged 36–59 were inconsistently classified across the included studies and were therefore excluded from subgroup analyses. Most studies defined age categories as either ‘young’ (16–35) or ‘older’ (≥ 60), with intermediate age groups rarely or inconsistently reported. Drivers with 4–10 years of driving experience were excluded from the subgroup meta-analyses because they were inconsistently categorised across the selected studies. To maintain the clarity and comparability of subgroup analyses, the meta-analysis focused on novice drivers (< 3 years) and experienced drivers (> 10 years), with definitions consistently applied. “Novice” drivers were classified as having less than 3 years of driving experience, while “experienced” drivers had more than 10 years. Additional subgroup analyses by study design, sample characteristics, or measurement methods were conducted to identify potential sources of heterogeneity. The chi-squared (χ^2) test assessed differences between subgroups, with statistical significance also defined at $p < 0.05$.

A pre-planned sensitivity analysis was undertaken to evaluate the robustness of the findings. This involved sequentially removing individual studies to assess their impact on the overall effect estimate. Publication bias was evaluated by visual inspection of funnel plots. When ten or more studies were included in a comparison, Egger’s linear regression test was applied to detect potential small-study effects. Studies contributing to funnel plot asymmetry with p-values below 0.05 were further scrutinised (Zhou et al., 2020).

Results

Table 1 summarises key studies on road sign comprehension, detailing sample characteristics, main findings, and noted limitations. Across diverse regions and populations, common factors such as age, education, and driving experience consistently influence comprehension. However, most studies have limited generalisability and rarely assess interventions to enhance understanding. These findings establish the empirical basis for the meta-analytic synthesis presented in the following sections.

Study characteristics

Nigeria has the highest number of articles at 3, followed by the Philippines with 2. All other countries (Pakistan, Jordan, Thailand, Ghana, and Israel) have a count of 1. Figure 1 highlights the differences and trends among the listed countries.

Based on continent, Africa has a total of 4, combining the numbers from Nigeria and Ghana. Asia has 6, aggregating the numbers from the Philippines, Pakistan, Jordan,

Table 1 An overview of studies on road sign comprehension

Author(s)/year	Sample Characteristics	Findings	Limitation/Research Gap
Robielos and Lin (2022)	−60 Filipino drivers and non-drivers in Metro Manila, Philippines	- Some traffic signs needed to meet comprehension standards. - Drivers had better comprehension than non-drivers. - Cognitive design features influenced comprehension.	- Limited to Metro Manila, Philippines, may not generalise to other regions. - Did not investigate interventions to improve comprehension of specific signs.
Imoh et al. (2021)	−467 drivers in Lagos, Nigeria	- There needs to be higher exposure of traffic signs to Lagos State road users. - Age, driving experience, and educational background influenced comprehension.	- Lack of specified sample characteristics limits generalizability. - Did not explore potential interventions to improve comprehension.
Shoaib et al. (2020)	−400 drivers in Lahore City, Pakistan	- Strong correlation between comprehensibility and age, education, and driving experience. −14% had high comprehensibility, 68% medium, and 18% low.	- Limited to Lahore City, Pakistan, may not generalise to other regions. - Did not explore specific interventions to improve comprehensibility.
Fernandez et al. (2020)	−535 Manila city drivers, Philippines	- Poor understanding of selected traffic signs among drivers. - Socio-economic background and driving characteristics influenced comprehension.	- Limited to Manila city drivers, may not represent broader populations in the Philippines. - Did not investigate specific reasons for poor comprehension.
Umar and Bashir (2019)	−190 drivers in Kano, Nigeria	-The majority of respondents were male and below 40 years old. -Good comprehension level overall, with variations based on personal characteristics.	- Limited to Kano, Nigeria, but may not be generalised to other regions. - Did not investigate specific interventions to improve comprehension.
Taamneh (2018)	−400 drivers in Irbid, Jordan	- Driving experience, marital status, age, and education influenced comprehension. - The decision tree algorithm identified influential factors.	- Limited to Irbid, Jordan, may not generalise to other regions. - The effectiveness of interventions was not investigated based on decision tree findings.
Choocharukul and Sriroongvikrai (2017)	−1,091 international tourists in Thailand	- Perception and awareness of road safety varied among tourists. - Text-based signs were easier to comprehend than symbolic signs. - Socio-economic and travel characteristics influenced comprehension.	- Limited to tourists in Thailand, may not generalise to other regions. - Did not investigate specific interventions to improve comprehension among tourists.
Boateng (2016)	−40 private drivers −60 mini-bus drivers −20 bus drivers −80 taxi drivers - Investigated the comprehensibility of 28 road signs in Sunyani Municipal, Ghana	- Overall satisfactory understanding of traffic signs in Sunyani Municipality, Ghana. - Educational background, age, and years driven influenced comprehension.	- Limited to drivers in Sunyani Municipality, Ghana, may not represent broader populations. - Did not investigate the effectiveness of specific training interventions.
Ben-Bassat and Shinar (2015)	−50 young drivers −50 older drivers - Tested comprehension of 28 Israeli road signs	- Young drivers outperformed older drivers in accuracy and response time. - Presentation mode did not affect comprehension. - Context increased comprehension time.	- Lack of effect of presentation mode on comprehension could suggest a need for further investigation into contextual factors affecting comprehension. - The study focused on Israeli road signs, which limit generalizability.
Makinde et al. (2012)	−185 drivers in Akure City, Nigeria	- Low understanding of traffic signs among drivers. - Age, education, and driving experience influenced comprehension.	- Limited to Akure City, Nigeria, may not generalise to other regions. - Did not investigate the effectiveness of specific training interventions.

Thailand, and Israel. Figure 2 shows the world map with highlighted countries.

The study by Choocharukul and Sriroongvikrai (2017) in Thailand had the largest sample size of 1,091 participants, underscoring a considerable research effort focused on international tourists. Meanwhile, studies such as Ben-Bassat and Shinar (2015) and Boateng (2016) included multiple subgroups within their samples, including various types of drivers and age cohorts, as depicted in the chart. These studies span various countries, reflecting global interest in understanding driving behaviours and assessing the effectiveness of road signs. Figure 3 shows the sample sizes

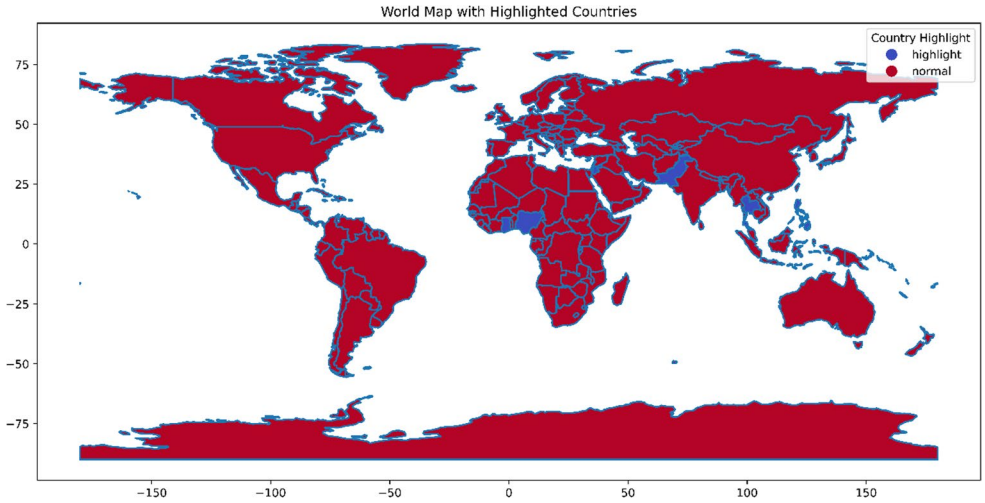

Fig. 2 World map with highlighted countries

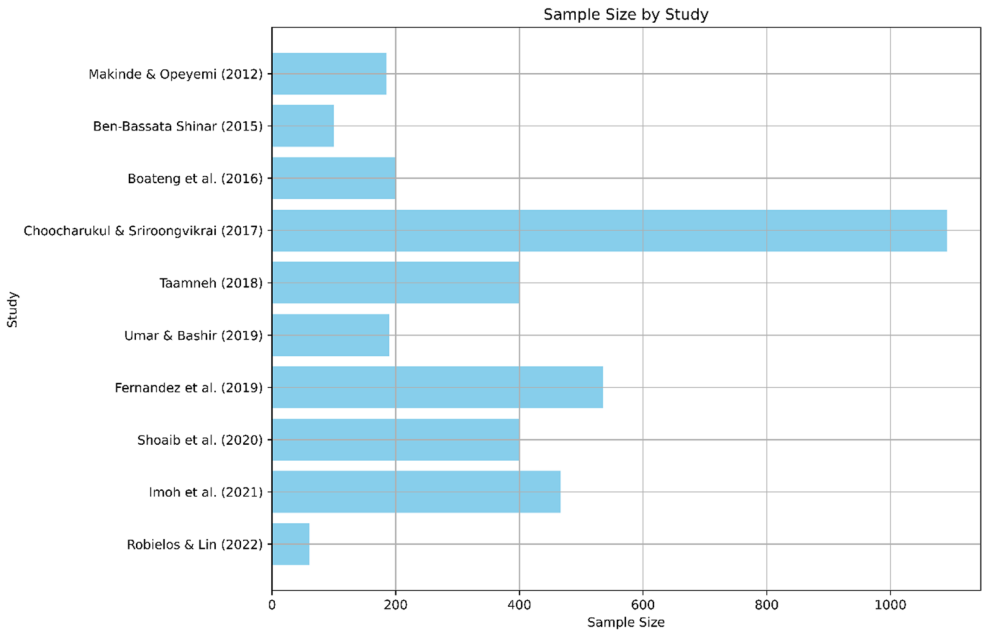

Fig. 3 Sample sizes across different studies on drivers and road sign comprehension in various locations

across different studies on drivers and road sign comprehension in various locations. The chart serves as an effective visual representation of the scale of each survey, offering insights into the extensive research conducted in this domain across diverse regions and demographic groups, facilitating comparisons of sample sizes in studies about drivers and road sign comprehension worldwide.

Description of studies included

The initial search yielded 20,682 papers. After deduplication, 1761 duplicates were removed, leaving 18,867 studies. The authors screened 18,867 articles for titles/abstracts and retrieved the full texts of 17 papers. After applying the eligibility criteria, 10 published studies on road sign comprehension were included (Fig. 4).

Gaps in current knowledge regarding road sign comprehension and factors influencing it

The existing studies collectively reveal several gaps in current knowledge regarding road sign comprehension and the factors influencing it:

1. Variability in Comprehension Levels: Studies conducted in locations such as Metro Manila, Lagos State, Lahore, Manila, Kano, and Akure indicate variability in comprehension levels among drivers and non-drivers. This suggests that comprehension factors may vary across geographical locations and demographic groups.
2. Impact of Personal Characteristics: Research consistently shows that personal characteristics — such as

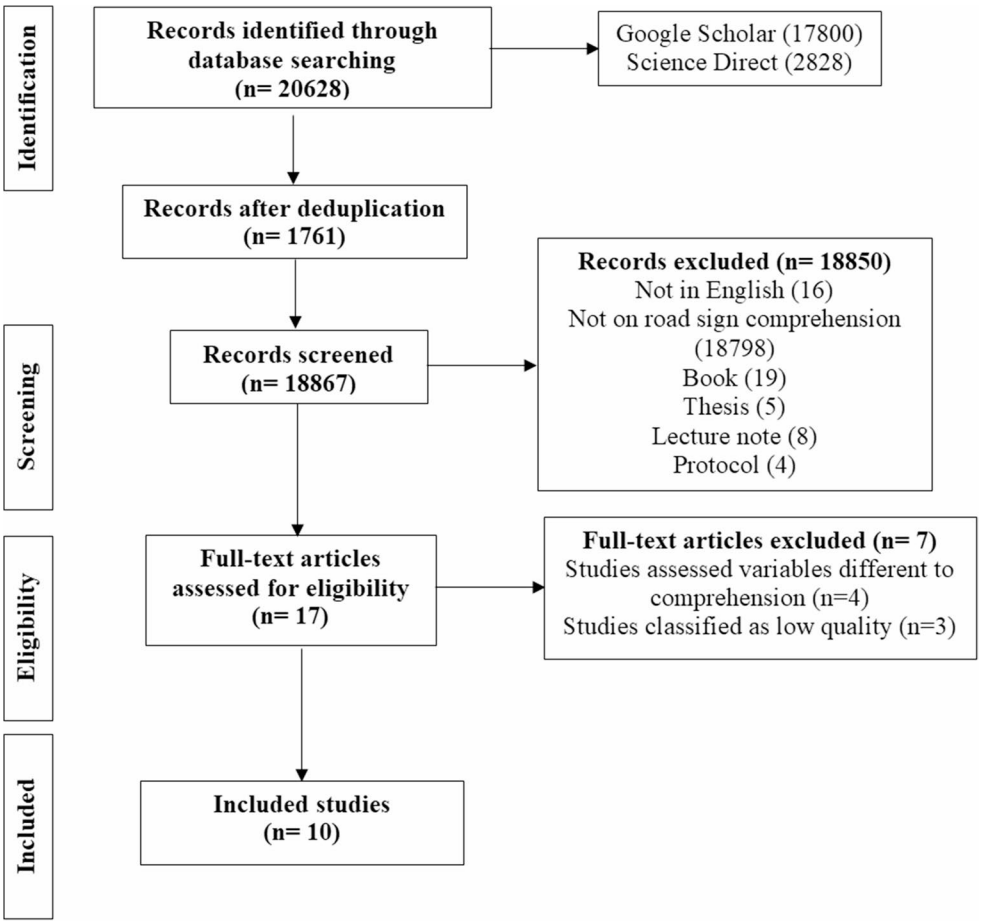

Fig. 4 PRISMA flow diagram

age, education, driving experience, and socio-economic background —significantly affect road sign comprehension. However, the extent of this impact may vary depending on the context, indicating a need for further exploration into specific demographic factors influencing comprehension.

3. Role of Cognitive Design Features: The study by Robielos and Lin (2022) emphasises the importance of cognitive design features, such as semantic distance, concreteness, complexity, and familiarity, in road sign comprehension. However, more research is needed to understand how these design features can be optimised to improve comprehension across different populations and contexts.
4. Effectiveness of Training and Sensitisation Programs: Several studies recommend implementing training and sensitisation programs to improve drivers' comprehension of road signs. However, more research is needed to evaluate the effectiveness of such programs, including their long-term impact on driving behaviour and road safety.
5. Cross-Cultural Differences: Studies involving international tourists in Thailand suggest that cultural and language differences may influence comprehension of road signs. Further research is needed to explore how cultural factors impact road sign comprehension, particularly in multicultural urban environments.
6. Need for Standardised Assessment Methods: Studies employ various assessment methods, such as matching-based comprehension tests, questionnaires, and decision-tree algorithms, but there is a lack of standardised approaches for evaluating road sign comprehension. Standardised assessment methods would facilitate comparisons across studies and regions, enabling a more comprehensive understanding of comprehension levels and influencing factors.
7. Influence of Road Environment: The study by Ben-Bassat and Shinar (2015) underscores the importance of considering the road environment in road sign comprehension. However, the study is minimal and analyses how road layout, visibility, and traffic conditions affect comprehension in real-world driving settings.
8. Integration of Technology: With technological advancements, there is potential to leverage tools such as virtual reality (VR) simulations and mobile

applications to enhance comprehension of road signs and driver training. However, limited research exists on the effectiveness of such technologies in improving comprehension and driving behaviour.

The existing studies provide valuable insights into road sign comprehension and influencing factors. However, several gaps warrant further research. Addressing these gaps would contribute to developing more effective strategies for enhancing road sign comprehension and promoting road safety (Ben-Bassat & Shinar, 2015; Boateng, 2016; Choocharukul & Sriroongvikrai, 2017; Fernandez et al., 2020; Imoh et al., 2021; Makinde et al., 2012; Robielos & Lin, 2022; Shoaib et al., 2020; Taamneh, 2018; Umar & Bashir, 2019).

Propose directions for future research aimed at improving road sign design, enhancing drivers' understanding, and promoting road safety

Based on the findings of the cited studies, here are some directions for future research aimed at improving road sign design, enhancing drivers' understanding, and promoting road safety:

1. Advanced Cognitive Design Features: Further research could explore new cognitive design aspects beyond familiarity, concreteness, complexity, and semantic distance. Investigating the effectiveness of incorporating elements such as colour psychology, visual hierarchy, and cultural relevance in road sign design may lead to improved comprehension and safety outcomes.
2. Contextual Signage Solutions: Conducting studies to assess the impact of contextual signage, such as dynamic signs that adapt to environmental conditions or driver characteristics, could enhance the effectiveness of road signs. Examining how contextual factors such as weather, time of day, and traffic density influence comprehension and responses to road signs would be beneficial.
3. Interactive Training and Sensitisation Programs: Research could focus on developing interactive training and sensitisation programs that leverage emerging technologies such as VR and augmented reality (AR). Assessing the effectiveness of these immersive training methods in improving road sign comprehension and driving behaviour could provide valuable insights for educational initiatives.
4. Cross-Cultural Signage Studies: Given road users' diverse cultural and linguistic backgrounds, conducting cross-cultural signage studies across regions and countries can help identify universal design principles and culturally specific considerations. Understanding how cultural factors influence road sign comprehension and adherence to traffic regulations is essential for global road safety initiatives.
5. Integration of Artificial Intelligence (AI) and Machine Learning: Exploring the application of AI and machine learning techniques to analyse large datasets of traffic sign comprehension could accelerate the development of predictive models. These models could identify patterns and trends in demographic factors, environmental conditions, and signage characteristics, guiding targeted interventions to improve road safety.
6. Evaluation of Policy Interventions: It is crucial to assess the effectiveness of policy interventions, such as mandatory retraining requirements for driver's license renewal or stricter enforcement of traffic laws, on-road sign comprehension, and compliance. Longitudinal studies tracking changes in driver behaviour and safety outcomes before and after policy implementation can provide policymakers with evidence-based recommendations.
7. User-Centred Design Approaches: Adopting user-centred design approaches that involve stakeholders, including drivers, traffic engineers, urban planners, and policymakers in the road sign design process can lead to more effective solutions. Collaborative research initiatives focused on co-designing and evaluating road signage prototypes with end users could yield signage systems that better meet the needs and preferences of diverse road user populations.
8. Smart Signage Technologies: Investigating the feasibility and impact of smart signage technologies, such as connected signs equipped with sensors and communication capabilities, could revolutionise road sign systems. Research in this area could explore how real-time data feedback, adaptive messaging, and personalised notifications can enhance the effectiveness of road signs and contribute to safer road environments.

Following these research directions, stakeholders can work towards designing more effective road sign systems that improve comprehension, promote compliance with traffic regulations, and ultimately enhance road safety for all users (Ben-Bassat & Shinar, 2015; Boateng, 2016; Choocharukul & Sriroongvikrai, 2017; Fernandez et al., 2020; Imoh et al., 2021; Makinde et al., 2012; Robielos & Lin, 2022; Shoaib et al., 2020; Taamneh, 2018; Umar & Bashir, 2019).

Provide valuable insights and recommendations for policymakers, transportation authorities, and researchers in traffic safety and signage design

Based on the findings from the cited studies, policymakers, transportation authorities, and researchers working in traffic safety and signage design can derive valuable insights and recommendations to improve road safety and enhance traffic sign comprehension (Pawar et al., 2023). The following are some key insights and recommendations:

1. Assessment and Improvement of Traffic Sign Comprehension.

i. Regular assessments of traffic sign comprehension among drivers and non-drivers should be conducted to identify areas of improvement.
ii. To enhance comprehension, prioritise redesigning traffic signs with low accuracy and slow matching time, especially those displayed in symbols.
iii. As demonstrated in the study, consider adding text to traffic signs displayed in symbols to improve matching accuracy and matching time.

2 Incorporation of Cognitive Design Features.

i. Emphasise the importance of cognitive design features such as semantic distance, concreteness, and familiarity in traffic sign design.
ii. Encourage traffic sign designers to prioritise these cognitive design features to ensure signs are easily understandable by a diverse range of road users.

3. Policy Recommendations.

i. Advocate for adopting the matching test methodology employed in the study as an obligatory retraining requirement for the renewal of driver's licenses by relevant government authorities, such as the Department of Transportation (Philippines).
ii. Establish traffic law courts to prosecute defaulters and enforce compliance with traffic regulations, as the study on Lagos State Road users recommended.

4. Educational and Training Initiatives.

i. Implement comprehensive training and sensitisation programs to educate drivers on the meanings of traffic signs and symbols, as the study of Lagos State Road users suggested.
ii. Driver education programs should be enhanced to improve comprehension of traffic signs, especially among novice drivers and those with limited driving experience.

5. Urban Planning and Infrastructure Development.

i. Integrate road signage considerations into urban planning processes and new infrastructure development, as recommended by the study on road signage comprehensibility in Lahore City, Pakistan.
ii. Ensure intergovernmental cooperation to address road safety issues and organise awareness-raising workshops for novice and regular drivers.

6. Use of Advanced Technologies.

i. Explore the potential of advanced technologies such as VR and AR for interactive training and sensitisation programs to enhance traffic sign comprehension.
ii. Investigate the feasibility of smart signage technologies, including connected signs with sensors and communication capabilities, to enhance real-time awareness about traffic situations and improve road safety.

7. Cross-Cultural Considerations.

i. Recognise the influence of cultural and socio-economic factors on traffic sign comprehension, as highlighted in studies conducted in various regions and countries.
ii. Tailor road signage solutions to diverse road user populations' specific needs and preferences, including international tourists, while ensuring compliance with local traffic laws and regulations.

8. Continuous Research and Evaluation.

i. Encourage ongoing research and evaluation efforts to assess the effectiveness of policy interventions, educational initiatives, and signage improvements in enhancing road safety and traffic sign comprehension.

ii. Share best practices and lessons learned across regions and nations to enable knowledge exchange and collaboration in traffic safety and sign design.

Following these recommendations and expanding upon the insights provided by the mentioned studies, stakeholders can strive towards creating safer road environments and reducing the occurrence of road accidents through enhanced traffic sign knowledge and compliance (Ben-Bassat & Shinar, 2015; Boateng, 2016; Choocharukul & Sriroongvikrai,

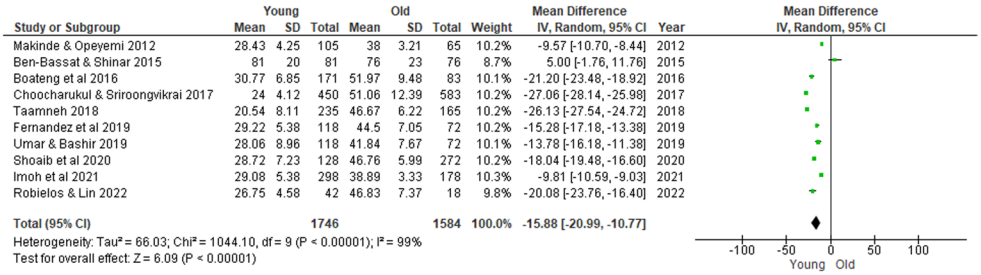

Fig. 5 Forest plot of effects of age on road sign comprehension

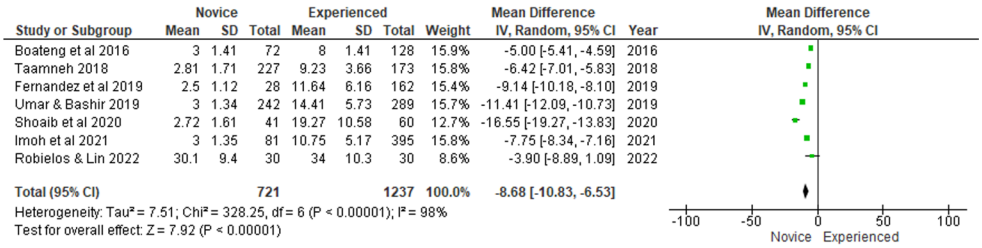

Fig. 6 Forest plot of effects of driving experience on road sign comprehension

2017; Fernandez et al., 2020; Imoh et al., 2021; Makinde et al., 2012; Robielos & Lin, 2022; Shoaib et al., 2020; Taamneh, 2018; Umar & Bashir, 2019).

Meta-analyses on age

The meta-analysis includes 3,330 participants, of whom 1,746 are young drivers and 1,584 are old drivers. Since the weight is 100%, it revealed that all studies were given equal importance in the analysis. The meta-analysis revealed a significant difference in the accident rates between young and older drivers. The total effect size, calculated with a 95% confidence interval (CI), was −15.88 [−20.99, −10.77] percentage points, indicating that, on average, young drivers were involved in 15.88% points more accidents than older drivers. Heterogeneity analysis indicated substantial variability among the included studies. The estimated Tau² was 66.03, and the Chi-square test yielded a value of 1044.10 with 9 degrees of freedom (df) ($P<0.00001$), indicating a high degree of heterogeneity among the studies. The I² statistic further supported this observation, indicating that 99% of the variability across studies was due to true differences rather than chance. The test for overall effect showed a statistically significant difference in accident rates between young and older drivers, with a Z-value of 6.09 ($P<0.00001$). This indicates that the overall effect of young drivers having more accidents was statistically significant across the included studies, as shown in Fig. 5.

Meta-analyses on driving experience

The meta-analysis includes 1,958 participants, of whom 721 are novice drivers and 1,237 are experienced drivers. As with the previous analysis, the weight is 100%, indicating equal weighting of studies. The meta-analysis revealed a significant difference in accident rates between novice and experienced drivers. The total effect size, calculated with a 95% confidence interval (CI), was −8.68 [−10.83, −6.53] percentage points, indicating that, on average, novice drivers were involved in 8.68% points more accidents than experienced drivers. Heterogeneity analysis indicated substantial variability among the included studies. The estimated Tau² was 7.51, and the Chi-square test yielded a value of 328.25 with 6 degrees of freedom (df) ($P<0.00001$), indicating a high degree of heterogeneity among the studies. The I² statistic further supported this observation, indicating that 98% of the variability across studies was due to true differences rather than chance. The test for overall effect showed a statistically significant difference in accident rates between novice and experienced drivers, with a Z-value of 7.92 ($P<0.00001$). This indicates that the overall effect of novice drivers having more accidents was statistically significant across the included studies, as shown in Fig. 6.

Although the meta-analyses were conducted separately by age and experience, cross-comparison of the pooled results revealed that younger drivers, who are often less experienced, showed comprehension deficits similar to those of novice drivers, suggesting a potential interaction between age and driving experience. This pattern underscores how limited experience may amplify age-related differences in comprehension, providing preliminary evidence of a combined influence on road sign understanding.

Sensitivity analyses

A sensitivity analysis was conducted for studies that assessed drivers' age and driving experience as outcomes to investigate potential biases. A positive estimate indicates

that younger drivers were implicated in more accidents. Only one study (Ben-Bassat & Shinar, 2015) yielded a positive value. The findings suggest that inexperienced drivers are more prone to accidents than seasoned drivers. Most studies, except for Robielos and Lin (2022), show a positive mean difference in crash rates, indicating that novice drivers are at a higher risk of accidents. Importantly, these results remained consistent across analyses of driving skills.

Publication bias

The funnel plot for both age and driving experience demonstrated no publication bias.

Discussions

The analysis of existing studies on road sign comprehension and influencing factors underscores the need for a comprehensive understanding of this critical aspect of road safety(Ben-Bassat & Shinar, 2015; Boateng, 2016; Choocharukul & Sriroongvikrai, 2017; Fernandez et al., 2020; Imoh et al., 2021; Makinde et al., 2012; Robielos & Lin, 2022; Shoaib et al., 2020; Taamneh, 2018; Umar & Bashir, 2019). These studies reveal significant variability in comprehension levels among drivers and non-drivers across different geographic locations, suggesting that factors influencing comprehension may vary by context. Personal characteristics such as age and driving experience consistently emerge as critical determinants of road sign comprehension, underscoring the importance of accounting for demographic factors in road safety interventions.

Findings from both meta-analyses suggest an interdependent relationship between age and driving experience. Younger, less experienced drivers tend to exhibit poorer sign comprehension due to limited exposure. In contrast, older but experienced drivers may compensate for cognitive decline through accumulated familiarity. This interaction highlights the compensatory role of experience in mitigating age-related deficits. Theoretically, this supports the cognitive compensation hypothesis, which posits that experiential learning can offset age-related declines in processing speed and working memory during driving tasks.

Furthermore, while cognitive design features such as semantic distance, concreteness, and familiarity play crucial roles in road sign comprehension, there is a need for further research to develop innovative design strategies tailored to different populations and contexts. Future research should prioritise developing advanced cognitive design features and contextual signage solutions to enhance the effectiveness of road signs and promote safer driving behaviours. Exploring innovative design elements such as colour psychology, visual hierarchy, and cultural relevance, researchers can identify strategies to optimise road sign comprehension across diverse populations (Emran et al., 2020).

Additionally, integrating emerging technologies like VR and AR into interactive training programs could revolutionise road safety education and provide valuable insights into effective learning methodologies (Orji et al., 2022; Robielos & Lin, 2022; Shoaib et al., 2020). Leveraging these technological advancements, policymakers and transportation authorities can improve the efficacy of road sign interventions and enhance overall road safety outcomes. Moreover, addressing cross-cultural differences in road sign comprehension and evaluating the effectiveness of policy interventions and training programs are critical steps toward improving road safety on a global scale (Boateng, 2016; Choocharukul & Sriroongvikrai, 2017; Gupta et al., 2021; Khan et al., 2015; Sârbescu et al., 2014; Son et al., 2016; Taubman – Ben-Ari et al., 2018; Ward et al., 2004). Through continual study, evaluation, and collaboration, stakeholders may strive to develop safer road environments and reduce the occurrence of road accidents worldwide.

This systematic review and meta-analysis provide valuable insights into the influence of age and driving experience on road sign comprehension. Young drivers typically have fewer years of driving experience than older drivers, which may lead to less developed driving skills and a reduced ability to anticipate and respond to potential hazards on the road (Ben-Bassat & Shinar, 2015; Makinde et al., 2012). Research suggests that young drivers may exhibit more risk-taking behaviours behind the wheel, such as speeding, distracted driving, and impaired driving, compared to older drivers (Boateng, 2016; de Winter & Kuipers, 2017; Lajunen et al., 2022; Lucidi et al., 2019; Shoaib et al., 2020). Consistently, older age was associated with reduced comprehension of road signs, underscoring the need for interventions tailored to older drivers' needs. This result aligns with Source, which has consistently shown that, as individuals age, there is a decline in cognitive abilities and visual processing, potentially affecting their ability to understand and interpret road signs effectively. This decline in comprehension among older drivers underscores the urgent need for interventions specifically designed for this demographic group. Interventions could include modifications to signage design, such as increasing font size or using more explicit symbols, to enhance visibility and understanding for older drivers.

Additionally, targeted educational programs to improve road sign comprehension among older adults could be implemented, providing them with the knowledge and skills necessary to navigate roads safely (Fausto et al., 2021). These findings underscore the importance of developing age-sensitive signage designs and educational programs to

mitigate potential safety risks associated with age-related declines in cognitive abilities and visual processing (Schulz et al., 2020). Interventions addressing the unique challenges older drivers face can help reduce safety risks and promote safer driving practices within this demographic.

Furthermore, the positive association between driving experience and road sign comprehension highlights the role of ongoing driver training and education in enhancing safe driving behaviours. It revealed that accumulated driving experience may contribute to a deeper understanding of road signs and their meanings, promoting safer driving practices. This implies that as individuals spend more time driving, they become more familiar with various traffic situations and signage conventions, leading to improved comprehension and safer driving practices (Charly & Mathew, 2023; Mustapha et al., 2022b). Novice drivers typically have less experience navigating various driving situations, which may contribute to higher accident rates (Robielos & Lin, 2022; Umar & Bashir, 2019). Similarly, research has shown that novice drivers may engage in riskier behaviours behind the wheel, such as speeding or distracted driving, compared to experienced drivers (Boateng, 2016; Shoaib et al., 2020). Studies have indicated that drivers with greater experience tend to exhibit better knowledge of road signs and are more adept at interpreting their meanings in different contexts (Shaaban, 2021; Shaaban et al., 2021; Tselentis et al., 2020). This enhanced understanding is attributed to exposure to diverse driving environments and situations, allowing experienced drivers to understand better signage and its significance for navigation and safety (Choi & Chong, 2022). Moreover, as drivers accumulate years behind the wheel, they gain practical insights and develop strategies for effective sign recognition and compliance, contributing to safer driving behaviours.

This study contributes to psychological and transportation research by quantitatively integrating two decades of evidence to clarify how age and experience jointly shape cognitive processing of traffic signs. The review advances theoretical understanding of driver cognition, informs user-centred signage design, and provides empirical evidence supporting differentiated safety interventions for novice and older drivers.

Limitations

This systematic review and meta-analysis synthesised evidence on the influence of age and driving experience on road sign comprehension; however, several limitations may affect the interpretation and generalizability of the findings. Although no geographical restrictions were applied, the final sample included studies from only seven countries, primarily due to the inclusion criteria: English-language publications, full-text availability, and the requirement for statistically analysable data. Although initial searches included broader databases, the final selection was limited to Google Scholar and ScienceDirect due to their extensive coverage of interdisciplinary and peer-reviewed literature. These databases yielded the most relevant studies based on the applied Boolean search strategy. Google Scholar captured cross-disciplinary research, while ScienceDirect provided access to peer-reviewed literature in key fields. Nonetheless, it is acknowledged that this approach may have excluded potentially relevant studies published in non-English languages or indexed in other databases. The dominance of specific regions also raises concerns about the applicability of findings to underrepresented contexts with different cultural, infrastructural, or educational characteristics. Future reviews may benefit from broader search strategies, including multilingual databases, grey literature, and collaboration with international scholars, to capture a more globally representative body of evidence.

Conclusions

This meta-analysis synthesised findings from ten studies that met the inclusion criteria, highlighting the significant influence of age and driving experience on road sign comprehension. Results indicated a consistent negative association between age and comprehension, with older individuals demonstrating lower comprehension than their younger counterparts. Conversely, driving experience was positively associated with sign comprehension, as more experienced drivers performed better than novice drivers. The results showed that older and novice drivers had significantly lower comprehension of road signs than younger and experienced drivers. These findings emphasise the need to design age- and experience-sensitive traffic signs and to implement educational interventions targeting vulnerable driver populations. Future studies should examine moderating variables, such as education level, cultural context, and visual literacy, that may affect how drivers interpret signage. Additionally, longitudinal studies are recommended to understand how comprehension evolves with continued driving exposure. These findings underscore the importance of accounting for individual differences when designing traffic signage and formulating road safety policies. Tailored interventions that address age-related cognitive changes and enhance the driving experience may improve comprehension and create safer road environments. Future research should examine potential moderating variables, such as education, cognitive ability, or cultural familiarity, to further clarify the relationship between driver characteristics and sign interpretation. Interventions should also be responsive to the diverse needs

of drivers across different age groups and experience levels to ensure accessibility and safety for all road users.

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Author contributions A.M. conceived and designed the study, performed the systematic review and meta-analysis, compiled and analysed the data, prepared the figures, and drafted the initial manuscript; M.M. supervised the study, validated the methodology, provided critical guidance on statistical analyses, and critically revised the manuscript for important intellectual content; N.S. contributed to data interpretation, assisted in synthesising literature on cognitive and psychological factors affecting road sign comprehension, and refined the theoretical framework; A.M.A.-R. provided technical support for meta-analytic procedures, contributed to the interpretation of results, and reviewed the results and discussion sections; A.A. contributed to data visualisation, assisted in drafting key sections, and reviewed and edited the manuscript. All authors reviewed and approved the final version of the manuscript.

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Declarations

Competing interests The authors declare no competing interests.

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