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Ergonomic factors affecting comprehension levels of traffic signs: A critical review ☆

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ABSTRACT

Comprehension of traffic signs is important to road safety. This review aims to study the extent to which road users in different countries comprehend traffic signs and to identify which ergonomic principles in traffic sign design can affect the levels of comprehension. We conducted an extensive literature review dealing with comprehension of public traffic signs directed at any road user. We searched Journal articles indexed by Scopus, ScienceDirect, and Web of Science. The search identified 35 articles that assessed the comprehension of 931 traffic signs in 26 countries, including six studies that tested the comprehension of new versus existing traffic signs. Various methods have been implemented to measure traffic signs' comprehension levels and assess traffic sign design's conformity to different ergonomic principles. Results indicate high variability in the comprehension levels of signs, e.g., signs such as "Road works" and "No U-turn" are highly comprehended (comprehension levels over 90 %), while other signs like "termination of road" are rarely comprehended by road users. Regarding the acceptable comprehension levels, 23.1 % of the assessed traffic signs achieved levels above 85 %; and 53.3 % of signs have comprehension levels lower than 67 %. On the other hand, twenty-four studies evaluated how traffic signs comply with ergonomic design principles. Incorporating ergonomic principles into the design of traffic signs can improve comprehension levels. However, apart from the *familiarity*, there is uncertainty about the ergonomic principles that could maximize the comprehension of traffic signs. Efforts should be made to ensure that different populations of road users sufficiently comprehend traffic signs.

Introduction

Traffic signs play an important role in creating a safer environment for drivers, bikers, and pedestrians (Oh et al., 2013). Signs, in general, convey semantic information through visual language (Bresciani, 2019) and thus help guide, regulate, and warn road users (Taylor et al., 2016); therefore, incorrect use of traffic signs may lead to road crashes, such as errors in making predictions about other road users' actions (Crundall and Kroll, 2018, Bañares et al., 2018). An accurate understanding of traffic signs is integral to road safety (Hou and Yang, 2020). Comprehension, defined here as the user's ability to interpret the

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meaning of a symbol accurately, is regarded as the most critical design factor for traffic signs (Dewar et al., 1994, Vilchez, 2019).

In evaluating and validating the levels of sign comprehension, international standards propose minimum levels of comprehensibility of traffic signs and means to ascertain the level that road users comprehend them. According to ISO 3864, signs are considered acceptable when 67 % of people in the target population correctly understand the sign in a comprehension test (International Standardization Organization, 2011). The ANSI Z535.3 standard proposed a stricter level of comprehension, indicating that for a sign to be acceptable, it should have a comprehension level of 85 % (American National Standards Institute, 2002). These non-compulsory standards include general guidance on the design or use of traffic signs but do not include criteria to ensure sign comprehension. Furthermore, as far as we know, there are no public records of traffic signs that comply with these comprehension standards.

Legislation in different countries defines design criteria for traffic signs, which usually include features such as size, shape, color, and location of signs. These criteria, while important especially to ensure sign perception; do not typically include guidelines for the design of icons, symbols or contents within the signs. Furthermore, the legislation does not demand that icons or symbols employed in traffic signs secure minimum levels of comprehension from road users. For example, in the United States, the Manual on Uniform Traffic Control Devices for Streets and Highways (MUTCD) requires uniformity in messages, locations, sizes, shapes, and colors (Federal Highway Administration - FHWA, 2003). In Latin America, countries like Colombia and Mexico require that the design of the traffic signs consider a combination of characteristics of size, colors, and shape; they recommend the use of pictograms and require that messages are simple (Hung, 2014, Ministerio de Transporte, 2015). In Europe, the Convention on Traffic Signs and Signals established the standard sizes, shapes, and colors to be used (United Nations, 2006). Although the Convention also defines symbols for the majority of the signs, there are still some differences in symbols and inscriptions between countries, which use the Vienna Convention. These requirements and recommendations suggest authorities are aware of the importance of road users comprehending the intended message of icons or symbols in traffic signs. However, the authorities do not necessarily know to what extent road users comprehend traffic signs in use; or whether some traffic signs have consistently shown a good or poor level of comprehension in different countries. Furthermore, there is no comprehensive information regarding the ergonomic principles of traffic sign design that have been shown to affect the comprehension of traffic signs. Having this type of information is crucial to those in charge of developing and approving traffic signs in different countries.

Several studies have evaluated the level of comprehension of numerous traffic signs in different countries and the ergonomic principles that can affect the observed level of comprehension. Despite this, currently, do not exist studies that have comprehensively analyzed this body of knowledge. Previous reports have indicated a wide range of comprehension levels of traffic signs within the same population. However, to our knowledge, there is no systematic assessment of comprehension levels of specific signs reported in different studied populations. In addition, we know that standard criteria have been long proposed to check if signs are well designed from the human factors perspective (Ben-Bassat and Shinar, 2006, Swanson et al., 1997, Sanders and McCormick, 1993). Nevertheless, no attempt has been made until now to assess among studies if some of these factors are more important than others and if complying with this set of criteria will improve the comprehension of traffic signs. It is, therefore, key to understanding to what degree road users comprehend traffic signs and knowing which reliable criteria exist to improve the level of comprehension of traffic signs.

The present review aims to study the extent to which road users comprehend contents (i.e., symbols, icons, inscriptions) within traffic signs and to identify the ergonomic principles of traffic sign design that may affect comprehension of traffic signs. We include in the present review manuscripts related to comprehension and design features of the icons or symbols used to warn, inform or recommend behaviors to road actors.

Methods

Search procedure

We designed a literature review of journal articles written in English dealing with comprehension and design of traffic signs. We were specifically interested in the visual design of the contents of traffic signs, that is, icons, symbols, or inscriptions within traffic signs. We reviewed numerous manuscripts which aimed to answer one or two of the following questions in a specific study population: 1) to what extent do people comprehend traffic signs?, moreover 2) what ergonomic principles of traffic signs' visual design affect their comprehension levels?. *Visual design* was defined as the graphical mapping of concepts structured meaningfully (Bertschi et al., 2011). Visualizations can be multimodal, composed of textual and visual elements such as lines, shapes, icons, or background images.

Articles focused on road safety and evaluating comprehension factors in traffic signs, regardless of the publication time frame, were searched on three electronic databases: Scopus, ScienceDirect, and Web of Science. In these databases, we sought articles that included in the title, abstract, or keywords four types of terms: road infrastructure, road actors, signaling, and comprehension (Table 1). We also identified manuscripts from personal databases and from checking references of articles deemed relevant to the review.

Table 1
List of terms used for the literature review, grouped into four different types.

Terms related to Road infrastructure		Terms related to Road Actors		Terms related to Signaling		Terms related to Comprehension
Road OR	AND	Pedestrian OR	AND	Symbol OR	AND	Comprehensi* OR
Traffic OR		Driver OR		Sign OR		Human factor OR
Intersection OR		Bicycle OR		Color OR		Ergonomic OR
Crosswalk OR		Cyclist OR		Shape OR		Safety OR
Cross-walk OR		Biker OR		Design OR		Recognition OR
Bridge OR		Motorcyclist OR		Traffic light OR		Understand
Path OR		Road Actor OR		Icon		
Sidewalk		Two-wheeler rider				

Selection of the articles

The articles identified in the search were selected in three subsequent steps based on the titles, abstracts, and the full review of the manuscripts. Two trained researchers reviewed all manuscripts independently using a protocol developed for this purpose. When there were differences, the researchers reached a consensus on the relevance of each manuscript to the present review. The same procedure using two researchers was used in the following stages of data extraction for quality assessment and documentation of study characteristics as used in previous studies (Navarro et al., 2018, Rodriguez and Barrero, 2017).

We excluded studies that: 1) were not conducted within the framework of road safety; 2) assess signs for private road use or industrial safety; 3) assess variable message signs (VMS) or Changeable Message Signs (CMSs); 4) focus on automatic recognition of signs (recognition of traffic signs images using algorithms), considering they are centered on the algorithm design; 5) were deemed to have low quality according to the quality criteria of the present review; and 6) were published as conference papers or proceedings, considering they were deemed work in progress.

Quality analysis of the articles

A critical assessment of the quality of the manuscripts was conducted based on a standard framework previously developed (Brewer et al., 2006). In total, we evaluated 12 quality factors, including two additional factors that were considered necessary for this review, namely, whether validation of the visual health conditions of participants was conducted; and whether a complete description of the conducted comprehension level analysis was provided. The factors were: 1. Presentation of the study objectives or presentation of the study hypothesis; 2. Use of measures to prevent learning effect, for example, the use of a randomized experimental design; 3. Justification of sample size; 4. Definition of the study target road users type (i.e., pedestrians, cyclists, drivers, motorcyclists - PTW (Powered two-Wheelers), MTW (Motorized two-wheeler)); 5. Description of the study population (e.g., age, occupation, country of origin); 6. Presentation of the inclusion and exclusion criteria of study participants; 7. Inclusion of an assessment of the visual health of participants, which is considered important to secure that participants had complete capacity to perceive the signs presented to them adequately; 8. Description of the signs being assessed in the study; 9. Description of the metrics used to assess independent variables of the study (i.e., the factors thought to affect comprehension level), if it applies; 10. Description of the data analysis procedures; 11. Description of the metric used to assess comprehension; 12. Report of the observed comprehension level for each assessed traffic sign.

Each factor was graded as one (1) when the study met the criteria and zero (0) when it failed to meet the criteria. When a factor did not apply to a specific study, the factor was marked as "NA", and the maximum number of points of the study is adjusted to exclude the factor. Two researchers independently reviewed each article, and the team discussed the ratings to gain consensus on any discrepancies. A single summary quality metric for each study was calculated as a percentage of the maximum number of points possible.

Studies with at least an average of 85 % were considered high quality. Studies with an average of 51 % and 84 % were considered medium quality. Studies that were at or below 50 % were considered low quality. These cut-offs were chosen based on previous reviews in the field of ergonomics (Brewer et al., 2006).

Information extraction and analysis

The following information was extracted from each study: the objective of the study, the country in which the study was conducted, study design, sample size, assessed road users (drivers, pedestrians, cyclists, motorcyclists, or two-wheeler riders, demographics of the study population (gender, age or experience in the road); number and type of signals assessed, the strategy used to present the sign to the user (i.e., cardboard card, images, and video), ergonomic principles, which were, thought to affect sign comprehension, and the methods used to assess those ergonomics principles, the method used to assess comprehension, and the comprehension level reported for each sign. Although we recorded other factors being investigated as potential factors affecting the observed sign comprehension levels (e.g., age, gender, or driving experience), our review focused on analyzing the potential effect of ergonomic principles on the visual sign design on comprehension levels.

The types of signs assessed were: (i) warning signs (i.e., those intended to communicate knowledge about potential hazards and how to avoid them, but can also be thought of as reminders that a hazard is present) (Vilchez, 2019); (ii) regulatory signs (i.e., those that are intended to inform road users of special obligations, restrictions or prohibitions they must comply with). This second type of sign includes the obligatory and prohibitory signs (i.e., those that inform about rules that road users must comply)(Castro et al., 2008); (iii) informatory or guidance signs (i.e., those that are intended to guide road users while they are traveling or to provide them with other information which may be useful).

The ergonomic principles considered in the present review were based on a previously proposed framework (Sanders and McCormick, 1993, Shinar et al., 2003, McDougall et al., 1999). Here, we summarize the definitions. *Familiarity* was defined as the frequency with which icons in signs have been encountered on the road or the frequency of encounter or use in people's daily lives (Ng and Chan, 2008, Ou and Liu, 2012). *Standardization* is defined as the extent to which the codes used for different dimensions, such as color and shape, are consistent for all signs (Ben-Bassat and Shinar, 2006). *Concreteness* is defined as the extent the sign depicts objects, which have obvious connections with the real world; for example, if the signs depict real objects, materials, or people, then those that do not depict real objects are considered abstract (Ng and Chan, 2008, Ou and Liu, 2012). *Compatibility* is defined as the correspondence between the sign and the message it represents. Compatibility includes (a) *Spatial compatibility*, i.e., the physical arrangement in space relative to the position of information and directions; (b) *Conceptual compatibility*, i.e., the extent to which symbols and codes conform to people's associations; (c) *Physical representation*, i.e., the similarity between the content of the sign and the reality it represents (Ben-Bassat and Shinar, 2006). *Meaningfulness* is defined as the extent people perceive icons in signs to be meaningful (Chan and Ng, 2010). *Simplicity* is defined as the extent signs use fewer elements or little detail in signs (Ou and Liu, 2012). Lastly, *Semantic closeness* or *Semantic distance* is a measure of the closeness of the relationship between the symbol and what it is intended to represent (McDougall et al., 1999).

Results

Identified studies

With the review strategy identified 8352 articles, 35 of which complied with the inclusion criteria of the present review (Fig. 1). The studies included in this review were conducted in 26 different countries, mainly from Europe (34.6 %) and Asia (38.5 %), but also America (11.5 %), Africa (7.7 %), and Oceania (7.7 %). All manuscripts evaluated comprehension of warning, regulatory, informatory (or guidance), and auxiliary signs. Of the 35 articles included, 91.4 % focused on vehicle drivers; the rest did not specifically define road users.

Quality assessment of studies

The quality assessment of the selected studies is presented in Table 2. Of the 35 studies identified in this review, five were considered high quality, and thirty were considered medium quality. Six additional studies are not included in the review because they were classified as low quality. The quality factors that were not more frequently met in the present review are the presentation of inclusion and exclusion criteria of participants (29.3 %) and the validation regarding the visual health conditions of the participants (24.4 %).

Instruments used to assess the comprehension of signs

The instruments used for measuring the level of comprehension are mostly self-reported or observational tests, which were implemented through surveys, questionnaires, or behavior tests. Two studies evaluated sign comprehension using eye tracking glasses (Babić et al., 2020, Babić et al., 2019), and a study evaluated sign comprehension using biometric indicators. Hou and Yang (2020) investigated neural indicators underlying traffic sign understanding by measuring event-related potentials (ERPs).

Regarding self-report tools, studies have used questions directly asking about a sign's meaning using multiple-choice or open-ended responses. In the case of multiple-choice questions, distractors are not frequently reported, making it difficult to assess biases in the reported comprehension levels due to poor distractors (Dewar et al., 1994).

In the case of questions using open-ended responses, participants were asked to write down the meaning of traffic signs (Taamneh and Alkheder, 2018, Jamson and Mrozek, 2017) or to indicate the meaning of different traffic signs throughout an interview (Hössinger and Berger, 2012, Kirmizioglu and Tuydes-Yaman, 2012). Answers are then graded as correct or incorrect using various scoring systems.

The most frequent proposed metric to grade responses uses four categories: correct and complete (coded as + 2), partially correct (+1), incorrect (0), or the opposite of the true sign meaning (-2) (Ben-Bassat and Shinar, 2006, Ben-Bassat and Shinar, 2015, Shinar et al., 2003, Bañares et al., 2018). Others have used similar scales, for example, coding correct (2), partially correct (1), incorrect (0) (Ben-Bassat, 2019, Dewar et al., 1994), or 'wrong' (0 points), 'partially correct' (0.5 points) and 'correct' (1 point) (Jamson and Mrozek, 2017), or signed is understood over 80 % (1 point), between 66–88 % (0.75 points), between 50–65 % (0.5 points) and the user understood the opposite meaning to the intended meaning (-1 point) (Ou and Liu, 2012).

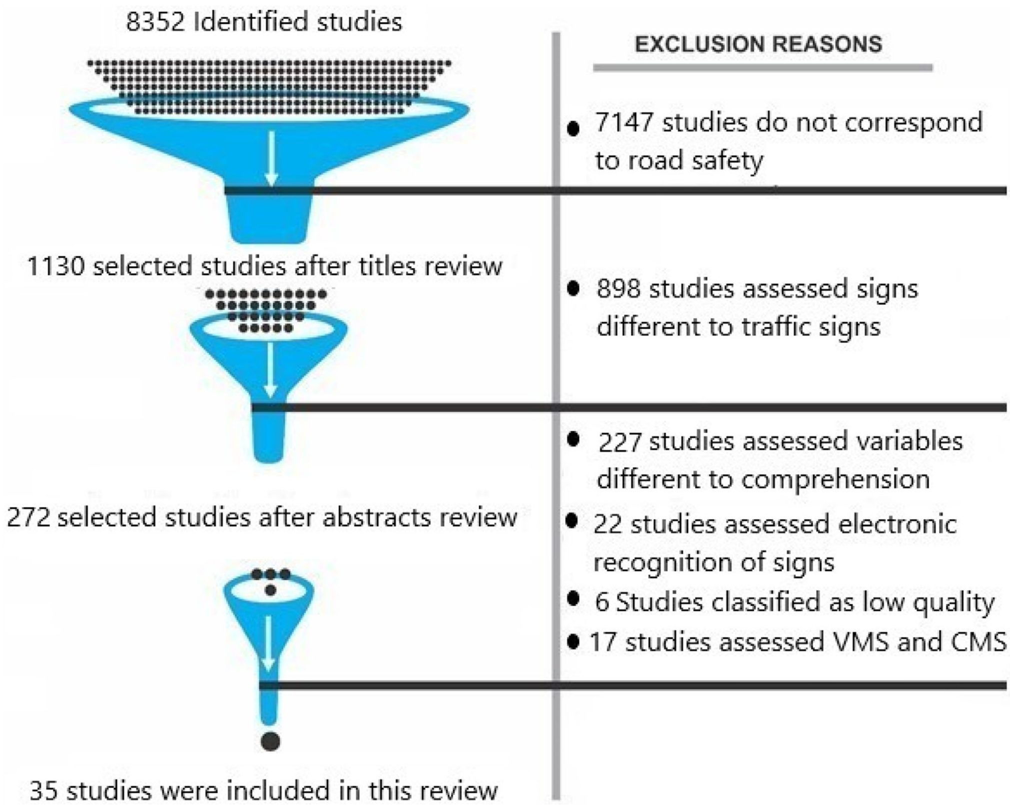

Fig. 1. The selection process of studies in the review.

For each traffic sign, the comprehension level of a group of participants is estimated by the proportion of all participants who have correct answers or the proportion of points obtained by participants out of the maximum number of points obtained if all participants' answers were correct.

Instruments used to assess ergonomic principles of comprehension

Self-reports, expert assessments, and eye-tracking systems have been used to assess ergonomic factors that potentially affect the level of comprehension of traffic signs. For self-reports, road users are typically directly asked to indicate how familiar, compatible, concrete (or abstract), simple, or meaningful they think a traffic sign is. For the assessment of familiarity, Taamneh and Alkheder (2018) and Kirmizioglu and Tuydes-Yaman (2012) used the following question: "have you ever seen this traffic sign?". To assess other ergonomic factors, authors typically provide participants with definitions or explanations of the ergonomic principles of interest, and participants rated on a numerical scale whether traffic signs comply with those principles (Ben-Bassat and Shinar, 2006, Ng and Chan, 2007).

Regarding expert evaluation, panels of professionals in topics like traffic engineering, ergonomics, psychology, or industrial design are typically asked to evaluate signs concerning its compliance with different design features. In the study by Ben-Bassat and Shinar (2006), for example, a group of human factors/ergonomics experts evaluated the level of standardization and compatibility of each sign in the study. The experts were asked to rate the signs using a 0 to 3 scale, where 0 meant the sign does not comply with any of the compatibility principles, 1 or 2 means the sign complies with one or two of the compatibility principles, and 3 means that the sign fully complies with all the compatibility principles. In another study, engineering and human factors experts evaluated several design aspects such as contents, graphics orientation, and sign layout (Bañares et al., 2018). The experts' ratings were used in the same study to determine the best design among various traffic sign alternatives (Bañares et al., 2018). The 'standardization' factor was assessed uniquely based on the number of countries in which traffic signs were presented out of the three countries participating in the study (Jamson and Mrozek, 2017). Also worth mentioning is the study by Ben-Bassat et al. (2019), in which conventional and alternative traffic sign designs were evaluated by twenty-seven human factors and ergonomics experts from 10 countries regarding compatibility, standardization, and familiarity.

Lastly, in the Babić et al. (2020) study, eye-tracking glasses were used to assess the level of familiarity of drivers with different signs. The authors hypothesized that drivers spend more time focusing on signs that are unfamiliar to them.

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Table 2
Quality assessment of identified manuscripts.

ID	Study	Quality factors											
		Quality Qualification	Defined objectives / Hypothesis	Randomized design	Justified Sample	Defined the road actors	Presented study population	Presented Inclusion and exclusion criteria	Assessed Visual health	Defined signs	Defined variables associated to ergonomic principles	Described statistical methods	Defined Comprehension Metric	Comprehension level
1	(Ben-Bassat and Shinar, 2015)	H = 92 %	1	1	1	1	1	1	0	1	1	1	1	1
2	(Maddahi et al., 2016)	H = 92 %	1	1	1	1	1	1	1	1	1	1	1	0
3	(Ou and Liu, 2012)	H = 92 %	1	1	1	1	1	1	1	1	1	1	1	0
4	(Babić et al., 2020)	H = 92 %	1	1	1	1	1	1	1	1	0	1	1	1
5	(Hou and Yang, 2020)	H = 91 %	1	1	1	1	1	0	1	1	Na	1	1	1
6	(Ben-Bassat et al., 2021)	M = 83 %	1	1	1	1	1	0	0	1	1	1	1	1
7	(Ben-Bassat, 2019)	M = 83 %	1	1	1	1	1	0	0	1	1	1	1	1
8	(Jamson and Mrozek, 2017)	M = 83 %	1	1	1	0	1	1	0	1	1	1	1	1
9	(Shinar and Vogelzang, 2013)	M = 83 %	1	1	1	0	1	1	0	1	1	1	1	1
10	(Shinar et al., 2003)	M = 83 %	1	1	1	1	1	0	0	1	1	1	1	1
11	(Ng and Chan, 2008)	M = 83 %	1	1	1	1	1	0	0	1	1	1	1	1
12	(Taamneh and Alkheder, 2018)	M = 83 %	1	0	1	1	1	1	0	1	1	1	1	1
13	(Roca et al., 2012)	M = 83 %	1	1	1	1	1	0	1	1	1	1	1	0
14	(Wontorczyk and Gaca, 2021)	M = 83 %	1	1	1	1	1	0	0	1	1	1	1	1
15	(Ng and Chan, 2007)	M = 83 %	1	1	0	0	1	1	1	1	1	1	1	1
16	(Yuan et al., 2014)	M = 83 %	1	1	1	1	1	0	0	1	1	1	1	1
17	(Makinde and Oluwasegunfunmi, 2014)	M = 82 %	1	1	1	1	1	0	0	1	Na	1	1	1
18	(Schulz et al., 2020)	M = 82 %	1	0	1	1	1	1	0	1	Na	1	1	1
19	(Al-Madani and Al-Janahi, 2002b)	M = 82 %	1	1	1	1	1	0	0	1	Na	1	1	1
20	(Al-Madani and Al-Janahi, 2002a)	M = 82 %	1	1	1	1	1	0	0	1	Na	1	1	1
21	(Al-Madani, 2000)	M = 82 %	1	1	1	1	1	0	0	1	Na	1	1	1
22	(Kirmizioglu and Tuydes-Yaman, 2012)	M = 75 %	1	1	1	1	1	0	0	1	1	0	1	1
23	(Ben-Bassat and Shinar, 2006)	M = 75 %	1	1	1	1	1	0	0	1	0	1	1	1
24	(Dewar et al., 1994)	M = 75 %	1	1	1	1	1	0	0	1	1	0	1	1
25	(Liu et al., 2019)	M = 75 %	1	0	0	0	1	1	1	1	1	1	1	1
26	(Taylor et al., 2016)	M = 73 %	1	1	1	1	0	1	0	1	Na	1	1	0
27	(Ben-Bassat et al., 2019)	M = 67 %	1	1	0	1	1	0	0	1	1	1	1	0
28	(Bañares et al., 2018)	M = 67 %	1	0	1	1	0	0	0	1	1	1	1	1
29	(Kim et al., 2009)	M = 67 %	1	0	1	1	1	0	0	1	1	1	1	0
30	(Al-Rousan and Umar, 2021)	M = 58 %	1	0	0	1	1	0	0	1	0	1	1	1
31	(Kline and Fuchs, 1993)	M = 67 %	1	1	0	1	1	0	1	1	0	1	1	0
32	(Fernandez et al., 2020)	M = 67 %	1	1	1	1	1	0	0	1	0	1	0	1

(continued on next page)

Table 2 (*continued*)

ID	Study	Quality factors											
		Quality Qualification	Defined objectives / Hypothesis	Randomized design	Justified Sample	Defined the road actors	Presented study population	Presented Inclusion and exclusion criteria	Assessed Visual health	Defined signs	Defined variables associated to ergonomic principles	Described statistical methods	Defined Comprehension Metric	Comprehension level
33	(Choocharukul and Sriroongvikrai, 2017)	M = 64 %	1	1	1	0	1	0	0	1	Na	1	1	0
34	(Charlton, 2006)	M = 64 %	1	1	0	1	1	0	0	1	Na	1	0	1
35	(Castro et al., 2008)	M = 58 %	1	1	0	0	1	0	1	1	0	1	1	0
36	(Razzak and Hasan, 2010)	L = 50 %	1	0	1	1	1	0	0	1	0	0	0	1
37	(Shang et al., 2021)	L = 50 %	1	0	0	1	1	0	1	1	0	1	0	0
38	(Bortei-Doku et al., 2017)	L = 45 %	1	0	1	1	1	0	0	0	Na	1	0	0
39	(Kaplan et al., 2018)	L = 42 %	1	0	1	0	1	0	0	0	1	1	0	0
40	(Viganò and Rovida, 2015)	L = 42 %	1	0	0	0	0	0	0	1	0	1	1	0
41	(Babić et al., 2019)	L = 42 %	1	0	0	0	1	0	0	1	0	1	1	0

Assessment of the studies: present (1), absence (0). Quality (minimum number of factors with compliance): H: High quality; M: Medium quality; L: Low quality.

Comprehension level of traffic signs

Twenty-two studies reported comprehension levels of a total of 931 different traffic signs. Most traffic signs that were comprehended by a good proportion of participants in one country (>67 %) were also comprehended by a good proportion of participants in other countries where the sign is used. In contrast, some traffic signs (12 traffic signs) were consistently comprehended by less than 67 % of the participants in two or more countries. However, other 92 signs showed acceptable comprehension levels in at least one country (>67 % of the participants understood the sign) while showing lower comprehension levels in at least another country. Overall, the results indicate high variability in the comprehension levels of the signs, where some traffic signs are highly comprehended while others are rarely comprehended by road users. Of the total traffic signs assessed, 23.1 % achieved comprehension levels equal to or above 85 %, and 23.6 % of the assessed traffic signs achieved levels between 67 % and 85 %. Other 53.3 % of the assessed traffic signs are comprehended by less than 67 % of the study population.

The maximum comprehension level was reported for the signs "Road works" (evaluated in seven studies and nine countries) and "No U-turn" (evaluated in five studies and seven countries), with comprehension levels over 90 % (Table 3) (Shinar et al., 2003, Ben-Bassat and Shinar, 2006, Taamneh and Alkheder, 2018, Shinar and Vogelzang, 2013, Ben-Bassat and Shinar, 2015). In contrast, the minimum comprehension level was reported for the sign "termination of road" in the study by Ben-Bassat and Shinar (2006) and the sign "level crossing with barrier ahead" in the study by Ng and Chan (2008). For the case of the traffic sign representing "End of speed limit", more than 10 % of the participants understood the opposite meaning (Ben-Bassat and Shinar, 2006, Shinar et al., 2003).

The traffic sign most frequently evaluated is "pedestrians crossing" (evaluated in 16 studies), and seven of those studies reported comprehension levels of over 90 %. The traffic signs used to convey this message share the same general features. They included an icon with multiple lines across a road and a legible image of a person walking. A traffic sign that does not share any of those characteristics is the one used by Makinde and Oluwasegunfunmi (2014), which was poorly comprehended (Table 3). Two other traffic signs related to the pedestrian crossing, which are generally similar to each other but do not share the same general features as the human figure in the icon, showed comprehension levels of 90 % and 16.6 %, even though both signs were reported to comply with ergonomic factors (Ng and Chan, 2008, Ben-Bassat and Shinar, 2015). These results could indicate the importance of 'compatibility' and 'standardization' with the desired message (Table 3).

The sign symbol representing "No entry" was understood by over 90 % of the participants in four different studies. Something to highlight is that the traffic sign evaluated in Jamson and Mrozek (2017) was well-comprehended. However, its symbol and colors are different from the sign used in other countries (Shinar et al., 2003, Kirmizioglu and Tuydes-Yaman, 2012, Taamneh and Alkheder, 2018, Ben-Bassat and Shinar, 2006, Choocharukul and Sriroongvikrai, 2017) (See Table 3). Regarding the warning traffic sign that represents "Road Work", six of the eight studies assessing this sign used a similar icon and the same orientation, and the comprehension levels are over 95 %. The other two signs, which have different features, did not reach such high comprehension levels but were still comprehended by more than 85 % of the participants (Taamneh and Alkheder, 2018). These results suggest that even significant variations in the traffic sign design can result in a good level of comprehension.

Comprehension level of new traffic signs proposals

Considering the high variability in the levels of comprehension of the traffic signs reported by different authors and the high percentage of misinterpretation of a few key traffic signs, some studies have focused on proposing alternative traffic sign designs. In this review, six studies compared comprehension levels of existing and alternative designs with the same intended message.

Bañares et al. (2018) proposed redesigned alternative road warning signs. The study measured the comprehension level for 40 road warning signs, including 21 new traffic signs, with original versions evaluated as poorly designed. The authors reported comprehension levels between 6.7 % and 92.2 % for the 40 existing signs and between 73.3 % and 96.7 % for the alternative designs. The redesigned traffic signs significantly improved comprehension levels, with a comprehensibility gap of up to 85.6 %. For example, the alternative design for the sign "Narrow Bridge" was better comprehended (92.2 % comprehension score) than the existing designs (6.7 % comprehension score). The novelty factors in the redesign were concentrated in the color background, small changes in the icons aiming to include the ergonomic principles in the display design, and the inclusion of text in all the alternatives. It is not possible to differentiate whether the observed positive effect in comprehension was due to changes made to the icons or the inclusion of text in the signs.

In contrast, Dewar et al. (1994) reported that the changes (modification and redesign) made to 13 existing standard signs did not improve comprehension. Nonetheless, three of them (two redesigned messages, "Mandatory Seat Belts," "Advanced Flagger," and one modified message, "Lane Reduction Transition") did result in better comprehension levels. The changes incorporated included a new spatial layout and enhanced legibility of the signs using an image-processing /redesign approach. Although it is difficult to indicate causally why the introduced changes did not result in systematic higher comprehension levels, it is important to highlight that Dewar et al. (1994) included a more heterogeneous study population coming from the USA and Canada and introduced changes to the visual design that were somewhat more radical than the study

Table 3
Comprehension level reported of the traffic signs most evaluated in this review.

Symbol	(Ng & Chan, 2008)	(Ben-Bassat & Shinar, 2015)	(Makinde and Oluwasegunfunmi , 2014)	(Shinar et al., 2003)	(S. Jamson & Mrozek, 2017)	(Shinar & Vogelzang, 2013)	(Taamneh & Alkheder, 2018)	(Ben-Bassat & Shinar, 2006	(Kirmizioglu & Tuydes-Yaman, 2012)	(Dewar, Kline, & Swanson, 1994)	(Al-Rousan and Umar, 2021)	(Bañares et al., 2018)	(Charlton, 2006)
Pedestrian Crossing (Warning)	26.61%	over 90%	50%	80%-90%	70%-80%	88%	92%	95%	97.52%	Image not reported 91.9%	95%	61.11%	~ 94%
Road narrows (Warning)	96.33%	88% - 98%	Not evaluated	80%-90%	Not evaluated	75%	Not evaluated	88 %	Reported, "Road narrow from left"	Image not reported 77.3%	Not evaluated	85.56%	Not evaluated
No entry (Regulatory)	Not evaluated	over 90%	Not evaluated	80%-90%	~ 90%	94%	85%	98%	77.8%	Not evaluated	Not evaluated	Not evaluated	Not evaluated
Two-way traffic (Warning)	99.08%	80%-90%	37.3%	Not evaluated	20%-30%	Not evaluated	76%	Not evaluated	74,15%	Image not reported 89,20%	Not evaluated	Not evaluated	Not evaluated
Road Work (Warning)	Not evaluated	100%	Not evaluated	over 90%	~ 98%	100%	89%	100%	96,69%	Not evaluated	Not evaluated	Not evaluated	100%

Note: The pictures in the table correspond to the reported in each article.

by Bañares et al. (2018). Furthermore, the comprehension levels of the existing traffic signs were already generally good (mean comprehension between 79.8 % and 81.4 %), which makes it more challenging to achieve improvements.

Shinar and Vogelzang (2013) assessed comprehension of 30 traffic signs with three variations: standard symbol-only, text-only, and symbol plus text. They found that the higher levels of comprehension were obtained for traffic signs with both text and symbol (95.2 % fully correct), and the lower levels of comprehension were obtained from signs with the symbol alone (53.1 % fully correct). In this study, the authors concluded that adding text improves comprehension and reduces the time it takes to comprehend the sign, especially unfamiliar signs. In general, adding text to the symbol improved comprehension. However, Choocharukul and Sriroongvikrai (2017) argued that such a statement would be valid only for local road users.

In Ben-Bassat et al. (2021) study, different licensed drivers from five countries were tested on the comprehension level of conventional and alternative traffic signs. The authors found that most of the alternative traffic signs (22 of 32 evaluated signs), which were said to comply with ergonomic principles of design, were better comprehended by drivers and had a lower comprehension response time. It is worth mentioning that in this study, some alternative signs (i.e., "No motorcycles" (45.4 %), "crossroad" (45.7 %), and "no stopping" (11.4 %)) did not yield higher comprehension levels than currently used signs (96.7 %, 51.5 %, and 36 %, respectively). Indicating that even a design that in theory complies with ergonomic principles may, in some cases, not guarantee comprehension; and that a sign already familiar to users may achieve higher levels of comprehension even if they are considered inferior in terms of compliance with ergonomic principles. Finally, Yuan et al. (2014), in the third stage, improved design of warning signs was provided; only the symbols within six warning signs were redesigned based on sign design features; their color and shape did not change; only the symbols were improved, they concluded that redesign of warning signs is more important than learning signs.

Assessment of compliance with ergonomic design principles

Twenty-four studies in the present review (68.6 %) assessed ergonomic design factors that are thought to affect comprehension of traffic signs. Familiarity is by far the single most studied factor that is thought to affect sign comprehension (91.7 % of 24 studies). In general, studies evaluated the familiarity of signs and three or four additional ergonomic factors. Other factors assessed were standardization, concreteness, spatial compatibility, conceptual compatibility, physical representation, meaningfulness, simplicity, and semantic closeness (Table 4). Out of the 24 studies that evaluated the design of traffic signs from an ergonomic perspective, only 14 also evaluated the association between design compliance with those ergonomic principles and comprehension. The other ten studies propose relations between ergonomic principles and the comprehension level of signs but did not present statistical association analyses. Furthermore, only eight studies from those that studied the association between design factors and comprehension did so through experimental studies, which allow for causal associations (Table 4). It is also worth noting that only seven studies simultaneously assessed various factors affecting comprehension.

Two studies showed a positive correlation among 11 studies assessing the single relationship between one of the ergonomic factors listed in Table 4 and comprehension level. Among the thirteen studies assessing the association of various ergonomic factors with comprehension simultaneously, five reported positive associations for all ergonomic factors assessed; and two studies reported at least one ergonomic factor with a negative association with comprehension. All the studies found a positive association relating to comprehension indicators in the case of familiarity. The result indicates that, in general, more familiarity will improve comprehension, although Shinar and Vogelzang (2013) indicated that familiarity' alone was not a guarantee of a good comprehension of traffic signs. The authors explained that several studies have shown that despite high levels of comprehension of the more familiar signs, there are significant differences in levels of sign comprehension depending on the sign and the characteristics of road users (e.g., novice, older, student drivers) (Shinar et al., 2003). Concerning 'Semantic closeness', four studies analyzed the correlation of comprehension with this factor, and two studies reported a positive relation (Ou and Liu, 2012, Maddahi et al., 2016).

The 'conceptual compatibility' factor was studied in seven studies (Table 4). Ben-Bassat (2019) reported a high and significant positive correlation between this principle and comprehension of traffic signs. In addition, Bañares et al. (2018) and Ben-Bassat and Shinar (2006) also showed positive correlations between this principle and comprehension of traffic signs. In contrast, Jamson and Mrozek (2017) reported that this 'conceptual compatibility' factor was the only principle that was not significantly associated with comprehension, although the authors did not report having presented surveyed participants with explanations about this concept. Other studies that assessed the 'conceptual compatibility' principle were Shinar et al. (2003), Ben-Bassat et al. (2019), and Ben-Bassat et al. (2021), who indicated in general that signs were comprehended best when they were consistent with ergonomic guidelines for display design, including the 'conceptual compatibility' principle.

Important results have also been reported in studies assessing the association between comprehension of traffic signs and the simultaneous adherence to multiple ergonomic principles of design of traffic signs (i.e., spatial compatibility, conceptual compatibility, physical representation, familiarity, and standardization). Ben-Bassat and Shinar (2006) reported that familiarity is the most important variable contributing to comprehension, followed by compatibility, although the partial effect of compatibility was only marginally significant. The authors highlighted that even the correlation between the unweighted mean score on all three principles (compatibility, familiarity, and standardization) and the signs' comprehension level (fully-correct responses) was not significantly greater than the correlation between comprehension and familiarity alone,

Table 4
Ergonomic factors assessed in the studies.

ID	Articles	# Factors evaluated	Ergonomic factors								
			Familiarity	Standardization	Concreteness	Spatial compatibility	Conceptual compatibility	Physical Representation	Meaningfulness	Simplicity	Semantic closeness
1	(Ben-Bassat and Shinar, 2015)	1	1	0	0	0	0	0	0	0	0
2	(Maddahi et al., 2016)	5*	1^{+++}	0	1^{+++}	0	0	0	1^{+++}	1^{+++}	1^{+++}
3	(Ou and Liu, 2012)	5*	1^{+}	0	1^{++}	0	0	0	1^{+++}	1^{-}	1^{+++}
4	(Babić et al., 2020)	1	1	0	0	0	0	0	0	0	0
6	(Ben-Bassat et al., 2021)	4	1	1	0	0	1	1	0	0	0
7	(Ben-Bassat, 2019)	2*	0	0	0	0	1^{+++}	1^{+++}	0	0	0
8	(Jamson and Mrozek, 2017)	5*	1	1^{s}	0	1^{s}	1^{ns}	1^{s}	0	0	0
9	(Shinar and Vogelzang, 2013)	1*	1^{+++}	0	0	0	0	0	0	0	0
10	(Shinar et al., 2003)	5*	1^{+++}	1[a]	0	1[a]	1[a]	1[a]	0	0	0
11	(Ng and Chan, 2008)	4*	1^{+}	0	1^{-}	0	0	0	1^{-}	1^{-}	0
12	(Taamneh and Alkheder, 2018)	1	1^{+}	0	0	0	0	0	0	0	0
13	(Roca et al., 2012)	1	0	0	1	0	0	0	0	0	0
14	(Wontorczyk and Gaca, 2021)	1	1	0	0	0	0	0	0	0	0
15	(Ng and Chan, 2007)	5*	1^{++}	0	1^{++}	0	0	0	1^{++}	1^{++}	1^{++}
16	(Yuan et al., 2014)	2	0	0	0	0	0	0	1	1	0
22	(Kirmizioglu and Tuydes-Yaman, 2012)	1	1[a]	0	0	0	0	0	0	0	0
23	(Ben-Bassat and Shinar, 2006)	4*	1^{+++}	1^{+++}	0	1^{+++}	1^{+++}	0	0	0	0
24	(Dewar et al., 1994)	1*	1^{++}	0	0	0	0	0	0	0	0
25	(Liu et al., 2019)	3	1	0	0	0	0	0	0	1	1
27	(Ben-Bassat et al., 2019)	4	1 [a]	1 [a]	0	0	1 [a]	1 [a]	0	0	0
28	(Bañares et al., 2018)	5*	1^{++}	1^{+}	0	1^{+}	1^{++}	1^{++}	0	0	0
29	(Kim et al., 2009)	1	1[a]	0	0	0	0	0	0	0	0
32	(Fernandez et al., 2020)	1	1	0	0	0	0	0	0	0	0
35	(Castro et al., 2008)	1	1[a]	0	0	0	0	0	0	0	0
The proportion of studies evaluating each factor			91.7 %	25.0 %	20.8 %	16.7 %	29.1 %	25.0 %	20.8 %	25.0 %	16.7 %

Note: 0: Indicates the study did not assess the factor. 1: Indicates the study assessed the factor; ($^{-}$ correlated negatively; $^{+}$slightly correlated ($r < 0.50$); $^{++}$ moderately correlated ($0.50 > r < 0.70$), $^{+++}$ highly correlated ($r >= 0.70$)); NS, not statistically significant; S, statistically significant with a level of significance $p < 0.05$). * Association analysis between ergonomic factors and comprehension was conducted. [a] Authors report positive associations but no measure of association is provided.

which emphasizes the importance of familiarity. In contrast, Jamson and Mrozek (2017) reported different results. They surveyed drivers in three countries to ascertain the comprehension of a range of traffic signs, each conformed in varying degrees and combinations to the ergonomic principles. They found that using any three principles was the most effective way to improve sign comprehension, and the most important principle was standardization. Overall, four of the five principles evaluated have a positive effect on comprehension, although it was reported that conceptual compatibility did not increase comprehension. Ou and Liu (2012) also analyzed the correlation between ergonomic principles of sign design and comprehension. The authors reported that the best predictor of comprehension was 'Semantic closeness.' In general, there was a trend according to which higher scores for the five sign design features implied higher levels of comprehension of traffic signs and lower levels of forgetfulness. Lastly, the authors highlight that the principle of semantic closeness had the greatest positive correlation with comprehension (Taiwanese group: r = 0.88; Vietnamese group: r = 0.80), followed by meaningfulness (Taiwanese group: r = 0.88; Vietnamese group: r = 0.60), concreteness (Taiwanese group: r = 0.86; Vietnamese group: r = 0.57), familiarity (Taiwanese group: r = 0.71; Vietnamese group: r = 0.42), and simplicity (Vietnamese group: r = 0.27). The detailed methodological characteristics of the articles included in this review are summarized in the Data Table accompanying this article.

Discussion

This review aimed to estimate the extent to which road users comprehend traffic signs and to identify the ergonomic principles of the visual design of traffic signs that affect comprehension levels. We found that while some public traffic signs are well comprehended among road users, in some cases, they are only comprehended by a small proportion of road users. Generally, 'indicatory and prohibition' signs, which convey information of high risk to road users, are more frequently comprehended than 'warning' signs and the signs with auxiliary information. Poor levels of comprehension were documented for key signs such as "Termination of road" (Ben-Bassat and Shinar, 2006, Shinar et al., 2003); "End of priority road" (Shinar et al., 2003, Shinar and Vogelzang, 2013, Ben-Bassat and Shinar, 2006, Kirmizioglu and Tuydes-Yaman, 2012, Taamneh and Alkheder, 2018); "Pedestrian on" or "Crossing road ahead" (Makinde and Oluwasegunfunmi, 2014, Bañares et al., 2018, Ng and Chan, 2008). There was even a case corresponding with the traffic sign "no entry for motorcycles" that was frequently misinterpreted as "motorcycles permitted" (Ben-Bassat and Shinar, 2006). These findings are concerning, considering they can directly affect the current level of risk faced by road users. Overall, these results raise questions about how governmental agencies are defining traffic sign design parameters in ways that contribute to sign comprehension. We also found important evidence that incorporating ergonomic principles in the design of traffic signs can positively affect their levels of comprehension.

The study by Bañares et al. (2018) found that comprehension levels can improve with better design (on average, 44 % for signs with messages such as "narrow bridge," "wheelchair crossing," and "reverse curve," among others) and that the improvement can be up to 85.6 %. Bañares et al. (2018) and other authors concluded that new signs were comprehended best when they were consistent with general ergonomic guidelines for display design (Ben-Bassat et al., 2021, Ben-Bassat et al., 2019, Shinar and Vogelzang, 2013). Furthermore, the more ergonomic principles become considered in the design, the better the level of comprehension regarding traffic signs are achieved, consistent with Jamson and Mrozek (2017), who recommend that traffic signs incorporate at least three ergonomic principles, with adherence to standardization being crucial for maximum comprehension. There is still some uncertainty, however, whether a single ergonomic principle of sign design is more important than others, and therefore, an integral design perspective should be considered when designing traffic signs.

It would appear that familiarity with the traffic sign is key to achieving good comprehension levels. This is expected because even if a sign does not inherently convey a clear message, road users can learn the intended message by experience. However, familiarity is not possible for new signs or for signs that are intended for road users that come from different backgrounds, for example, in the case of tourists driving cars in different contexts. Ben-Bassat and Shinar (2006) present examples of signs that are comprehended 100 % in the population where they are original from, and have low comprehension levels in other localities. Furthermore, it is clear that that familiarity may be potentiated by other factors, such as simplicity. For example, if signs are simple, they may be easier to memorize and will likely to become familiar in less time. This finding highlights the importance of going beyond efforts to incorporate ergonomics components into the design of traffic signs. Efforts should include pilot-testing signs among heterogeneous populations according to the expected users of the traffic signs and perhaps also generating campaigns to inform the public about the meaning of them (Silva et al., 2020, Obregón-Biosca et al., 2018).

Methodologically, this review found that most frequently, studies assessed three or four ergonomic factors of visual sign design. For example, some studies assessed familiarity, compatibility, and standardization (Ben-Bassat and Shinar, 2006, Jamson and Mrozek, 2017). Other studies focused on simplicity, concreteness, meaningfulness, and semantic closeness (Maddahi et al., 2016, Ou and Liu, 2012). This partial evaluation of ergonomic principles is understandable, considering that some of these factors are highly related (Ou and Liu (2012). For example, one can say that compatibility includes aspects of meaningfulness and semantic closeness; and standardization may contain facets of concreteness and simplicity. Altogether, it is recommended that the ergonomics assessment of traffic signs incorporate as many components as possible, even if some of those components relate to each other.

Another key finding is that most (91.4 %) studies focused on vehicle drivers. This focus is understandable, considering drivers are in charge of controlling most of the energy that is delivered in road crashes. However, drivers are only 64 % of the road users (World Health Organization, 2018), and drivers must respond to actions not only from other drivers but also from other road users. Furthermore, it raises the question of whether other road users understand signs intended for drivers; and if those other road users can predict vehicle drivers' behaviors when they can understand signs intended for drivers.

This review has various limitations. The results, in general, are not generalizable to places other than those where the studies were conducted, especially considering that most of the studies are concentrated in Asia and Europe, although there are studies in all continents. Also, the review includes only studies that evaluated the variable comprehension of public traffic signs. This is key because any incompatibility between public and private signs can be a potential source of confusion for road actors. We recommend this aspect to be a subject of study in the future. Also, this review focuses only on a single step (i.e., comprehension) of all the required cognitive processes (Kaye et al., 2013), from perceiving a traffic sign to eventually taking preventive actions. In this review, we were not concerned with whether the required infrastructure was in place for the traffic signs to be clearly visible. Furthermore, considering the typical study design in the reviewed literature, we assume all the traffic signs can be seen in detail and read with enough time to be comprehended, which may be a crucial factor in some real-life circumstances.

In conclusion, in this review, we found that traffic signs are often not comprehended by road users. Some key traffic signs have shown high levels of comprehension in different countries, while others are well comprehended only in specific contexts. The use of ergonomic design principles can improve levels of comprehension of traffic signs. Efforts must be guaranteed to incorporate ergonomic principles in the design of traffic signs and to conduct sufficient comprehension testing in heterogeneous populations of road users.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix A. Supplementary material

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ijtst.2022.08.004.

References

Al-Madani, H., Al-Janahi, A.-R., 2002a. Assessment of drivers' comprehension of traffic signs based on their traffic, personal and social characteristics. Transport. Res. Part F: Traffic Psychol. Behav. 5, 63–76.

Al-Madani, H., Al-Janahi, A.R., 2002b. Role of drivers' personal characteristics in understanding traffic sign symbols. Accid. Anal. Prev. 34, 185–196.

Al-madani, H., 2000. Influence of drivers' comprehension of posted signs on their safety related characteristics. Accid. Anal. Prev. 32, 575–581.

Al-Rousan, T.M., Umar, A.A., 2021. Assessment of traffic sign comprehension levels among drivers in the Emirate of Abu Dhabi. UAE. *Infrastructures* 6, 122.

AMERICAN NATIONAL STANDARDS INSTITUTE 2002. Criteria for Safety Symbols - ANSI Z535.3.

Babić, D., Tremski, Š., Babić, D., 2019. Investigation of traffic signs understanding - eye tracking case study. Tehnicki Vjesnik 26, 29–35.

Babić, D., Dijanić, H., Jakob, L., Babić, D., Garcia-Garzon, E., 2020. Driver eye movements in relation to unfamiliar traffic signs: an eye tracking study. Appl. Ergon. 89, 103191.

Bañares, J.R., Caballes, S.A., Serdan, M.J., Liggayu, A.T., Bongo, M.F., 2018. A comprehension-based ergonomic redesign of Philippine road warning signs. Int. J. Ind. Ergon. 65, 17–25.

Ben-Bassat, T., Shinar, D., 2006. Ergonomic guidelines for traffic sign design increase sign comprehension. Hum. Factors 48, 182–195.

Ben-Bassat, T., Shinar, D., 2015. The effect of context and drivers' age on highway traffic signs comprehension. Transportation Research Part F: Traffic Psychology and Behaviour 33, 117–127.

Ben-Bassat, T., Shinar, D., Almqvist, R., Caird, J.K., Dewar, R.E., Lehtonen, E., Salmon, P.M., Sinclair, M., Summala, H., Zakowska, L., Liberman, G., 2019. Expert evaluation of traffic signs: conventional vs. alternative designs. Ergonomics 62, 734–747.

Ben-Bassat, T., Shinar, D., Caird, J.K., Dewar, R.E., Lehtonen, E., Sinclair, M., Zakowska, L., Simmons, S., Liberman, G., Pronin, M., 2021. Ergonomic design improves cross-cultural road sign comprehension. Transport. Res. Part F: Traffic Psychol. Behav. 78, 267–279.

Ben-bassat, T., 2019. Are ergonomically designed road signs more easily learned? Appl. Ergon. 78, 137–147.

BERTSCHI, S., BRESCIANI, S., CRAWFORD, T., GOEBEL, R., KIENREICH, W., LINDNER, M., SABOL, V. & VANDE MOERE, A. 2011. *What is Knowledge Visualization? Perspectives on an Emerging Discipline*.

Bortei-Doku, S., Kaplan, S., Prato, C.G., Nielsen, O.A., 2017. Road signage comprehension and overload: the role of driving style and need for closure. Transp. Res. Procedia 24, 442–449.

Bresciani, S., 2019. Visual design thinking: a collaborative dimensions framework to profile visualisations. Des. Stud. 63, 92–124.

Brewer, S., van Eerd, D., Amick, B.C., Irvin, E., Daum, K.M., Gerr, F., Moore, J.S., Cullen, K., Rempel, D., 2006. Workplace interventions to prevent musculoskeletal and visual symptoms and disorders among computer users: A systematic review. J. Occup. Rehabil. 16, 325–358.

Castro, C., Moreno-Ríos, S., Tornay, F., Vargas, C., 2008. Mental representations of obligatory and prohibitory traffic signs. Acta Psychol. 129, 8–17.

Chan, A.H.S., Ng, A.W.Y., 2010. Investigation of guessability of industrial safety signs: effects of prospective-user factors and cognitive sign features. Int. J. Ind. Ergon. 40, 689–697.

Charlton, S.G., 2006. Conspicuity, memorability, comprehension, and priming in road hazard warning signs. Accid. Anal. Prev. 38, 496–506.

Choocharukul, K., Sriroongvikrai, K., 2017. Road safety awareness and comprehension of road signs from international tourist's perspectives: a case study of Thailand. Transp. Res. Procedia 25, 4518–4528.

Crundall, D., Kroll, V., 2018. Prediction and perception of hazards in professional drivers: does hazard perception skill differ between safe and less-safe fire-appliance drivers? Accid Anal Prev 121, 335–346.

Dewar, R.E., Kline, D.W., Swanson, H.A., 1994. Age differences in comprehension of traffic sign symbols. Transp. Res. Rec.

FEDERAL HIGHWAY ADMINISTRATION - FHWA 2003. Manual on Uniform Traffic Control Devices for Streets and Highways, 2003 Edition. mutcd.fhwa.dot.gov/.

Fernandez, J.J., Paringit, M.C., Salvador, J.R., Lucero, P.I., Galupino, J.G., 2020. Understanding of traffic signs by drivers in the city of Manila, Philippines. Transp. Res. Procedia 48, 3037–3048.
Hössinger, R., Berger, W.J., 2012. Comprehension of new instructions for car drivers in merging areas. Transport. Res. Part F: Traffic Psychol. Behav. 15, 152–161.
Hou, G., Yang, J., 2020. Measuring and examining traffic sign comprehension with event-related potentials. Cogn. Technol. Work.
HUNG, C. 2014. Manual de señalización vial y dispositivos de seguridad. *Secretaría de Comunicaciones y Transportes,* 770.
INTERNATIONAL STANDARDIZATION ORGANIZATION 2011. Graphical symbols – Safety colours and safety signs – Part 1: Design principles for safety signs and safety markings - ISO 3864-1:2011.
Jamson, S., Mrozek, M., 2017. Is three the magic number? the role of ergonomic principles in cross country comprehension of road traffic signs. Ergonomics 60, 1024–1031.
Kaplan, S., Bortei-Doku, S., Prato, C.G., 2018. The relation between the perception of safe traffic and the comprehension of road signs in conditions of ambiguous and redundant information. Transport. Res. Part F: Traffic Psychol. Behav. 55, 415–425.
Kaye, S.-A., White, M.J., Lewis, I.M., 2013. Individual differences in drivers' cognitive processing of road safety messages. Accid. Anal. Prev. 50, 272–281.
Kim, S., Ulfarsson, G.F., Anton, K.R., 2009. Traffic sign comprehensibility in an aging society a study of "photo-enforced traffic signal ahead" signage. Transp. Res. Rec., 81–88
Kirmizioglu, E., Tuydes-Yaman, H., 2012. Comprehensibility of traffic signs among urban drivers in Turkey. Accid. Anal. Prev. 45, 131–141.
Kline, D., Fuchs, P., 1993. The visibility of symbolic highway signs can be increased among drivers of all ages. Hum. Factors 35, 25–34.
Liu, J., Wen, H.Y., Zhu, D.C., Kumfer, W., 2019. Investigation of the contributory factors to the guessability of traffic signs. Int. J. Environ. Res. Public Health 16, 21.
Maddahi, H., Pouyakian, M., Ghomsheh, F.T., Piri, L., Osqueizadeh, R., 2016. Design and cognitive evaluation of 6 dynamic lane departure warning symbols. Traffic Inj. Prev. 17, 842–847.
Makinde, O.O., Oluwasegunfunmi, V., 2014. Comprehension of traffic control devices amongst urban drivers–a study of Ado-Ekiti, Ekiti State, Nigeria. Eur. J. Eng. Technol. 2, 9–19.
McDougall, S.J.P., Curry, M.B., de Bruijn, O., 1999. Measuring symbol and icon characteristics: Norms for concreteness, complexity, meaningfulness, familiarity, and semantic distance for 239 symbols. Behav. Res. Methods, Instruments, Comput. 31, 487–519.
MINISTERIO DE TRANSPORTE 2015. Manual de señalización vial de dispositivos uniformes para la regulación de tránsito en las vías de Colombia. *In:* TRANSPORTE, M. D. (ed.)
Navarro, J., Reynaud, E., Osiurak, F., 2018. Neuroergonomics of car driving: a critical meta-analysis of neuroimaging data on the human brain behind the wheel. Neurosci. Biobehav. Rev. 95, 464–479.
Ng, A.W.Y., Chan, A.H.S., 2007. The guessability of traffic signs: effects of prospective-user factors and sign design features. Accid. Anal. Prev. 39, 1245–1257.
Ng, A.W.Y., Chan, A.H.S., 2008. The effects of driver factors and sign design features on the comprehensibility of traffic signs. J. Saf. Res. 39, 321–328.
Obregón-Biosca, S.A., Betanzo-Quezada, E., Romero-Navarrete, J.A., Ríos-Nuñez, M., 2018. Rating road traffic education. Transport. Res. Part F: Traffic Psychol. Behav. 56, 33–45.
Oh, K.H., Rogoff, A., Smith-Jackson, T., 2013. The effects of sign design features on bicycle pictorial symbols for bicycling facility signs. Appl. Ergon. 44, 990–995.
Ou, Y.-K., Liu, Y.-C., 2012. Effects of sign design features and training on comprehension of traffic signs in Taiwanese and Vietnamese user groups. Int. J. Ind. Ergon. 42, 1–7.
Razzak, A., Hasan, T., 2010. Motorist understanding of traffic signs: a study in Dhaka city. J. Civil Eng. (IEB) 38, 17–29.
Roca, J., Castro, C., Bueno, M., Moreno-Rios, S., 2012. A driving-emulation task to study the integration of goals with obligatory and prohibitory traffic signs. Appl. Ergon. 43, 81–88.
Rodriguez, A.C., Barrero, L.H., 2017. Job rotation: Effects on muscular activity variability. Appl. Ergon. 60, 83–92.
Sanders, M.S., McCormick, E.J., 1993. Human Factors in Engineering and Design.
Schulz, P., Labudda, K., Bertke, V., Bellgardt, S., Boedeker, S., Spannhorst, S., Kreisel, S.H., Driessen, M., Beblo, T., Toepper, M., 2020. Age effects on traffic sign comprehension. IATSS Res. 44, 103–110.
Shang, T, Lu, H, Wu, P, Wei, Y, 2021. Eye-tracking evaluation of exit advance guide signs in highway tunnels in familiar and unfamiliar drivers. Int. J. Environ. Res. Public Health 18. https://doi.org/10.3390/ijerph18136820.
Shinar, D., Dewar, R., Summala, H., Zakowska, L., 2003. Traffic sign symbol comprehension: a cross-cultural study. Ergonomics 46, 1549–1565.
Shinar, D., Vogelzang, M., 2013. Comprehension of traffic signs with symbolic versus text displays. Transport. Res. Part F: Traffic Psychol. Behav. 18, 72–82.
Silva, T.C., Laiz, M.T., Tabak, B.M., 2020. Traffic campaigns and overconfidence: an experimental approach. Accid. Anal. Prev. 146, 105694.
Swanson, H., Kline, D. W. & Dewar, R. E. Guidelines for traffic sign symbols. IPENZ Annual Conference 1997, Proceedings of: Engineering our nation's future; Volume 1; Papers presented in the technical programme of the IPENZ Annual Conference held in Wellington, February 7-10, 1997, 1997. Institution of Professional Engineers New Zealand, 239.
Taamneh, M., Alkheder, S., 2018. Traffic sign perception among Jordanian drivers: an evaluation study. Transp. Policy 66, 17–29.
Taylor, B., Chekaluk, E., Irwin, J., 2016. Reading the situation: The relationship between dyslexia and situational awareness for road sign information. Transport. Res. Part F: Traffic Psychol. Behav. 36, 6–13.
UNITED NATIONS 2006. Convention on Road Signs and Signals of 1968 European Agreement Supplementing the Convention and Protocol on Road Markings, Additional to the European Agreement - 2006 consolidated versions.
Viganò, R., Rovida, E., 2015. A proposed method about the design of road signs. J. Transport. Saf. Security 7, 56–75.
Vilchez, J.L., 2019. Mental representation of traffic signs and their classification: warning signs. Transport. Res. Part F: Traffic Psychol. Behav. 64, 447–462.
Wontorczyk, A., Gaca, S., 2021. Study on the relationship between drivers' personal characters and non-standard traffic signs comprehensibility. Int. J. Environ. Res. Public Health 18, 2678.
WORLD HEALTH ORGANIZATION 2018. Global status report on road safety 2018. Geneva: World Health Organization
Yuan, L., Ma, Y.F., Lei, Z.Y., Xu, P., 2014. Driver's comprehension and improvement of warning signs. Adv. Mech. Eng. 9.