Using eye tracking to study reading landscape: a systematic review

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ABSTRACT
More studies have understood landscape as a perceived entity since the European Landscape Convention was approved in 2004. This article adopts a systematic review approach in line with the PRISMA statement to delineate the utilization of eye tracking in studying landscapes. A comprehensive analysis of 55 studies sourced from the Web of Science and Scopus databases was conducted. Various aspects were scrutinized, encompassing landscape attributes, media employed for landscape representation, eye tracking data visualizations, and eye tracking metrics. The prevalence of eye tracking usage in landscape studies has notably increased since 1998, with research conducted across all continents. The most studied aspects of the landscape are saliency and specifics of particular types of landscape. Amongst the varied media used to represent landscape, photographs reign supreme, while heatmaps prominently feature as a means to visualize eye tracking data. The spectrum of metrics applied is extensive, showcasing distinct suitability for specific landscape attributes. Drawing from this review, recommendations for prospective research directions are outlined. The insights garnered from this review stand to serve as a valuable overview for researchers delving into the realm of reading landscape.

KEYWORDS
landscape perception; reading landscape; eye tracking; systematic review

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1. Introduction

Landscape can be perceived as a dynamic entity, a segment of the environment infused with natural and social elements, appearing distinct to various individuals. Different aspects of the landscape hold unique personal meanings for observers, with perception shaped by aesthetic values and prior experiences. This perspective gained traction following the publication of the European Landscape Convention in 2000, which defined landscape as "an area perceived by people, characterized by the interplay of natural and/or human factors" (Council of Europe 2000). Subsequently, an increasing number of studies have honed in on reading landscape (Khaledi et al. 2022).

Understanding reading landscape holds significant utility in establishing perceptual priorities based on what people perceive and discern in the landscape. It aids responsible engagement with the landscape and informs place-based education initiatives (Smith 2002). Moreover, it serves as a potent tool to comprehend and interpret the landscape.

Various methodologies have been devised to study reading landscape. One approach draws from Kevin Lynch's (1960) method of studying city perception, where individuals sketch the cityscape and articulate their thoughts about their drawings. Another approach involves the observation and assessment of photographs, employed to ascertain aspects such as landscape attractiveness or beauty (Kaplan et al. 1989). Technological advancements have expanded the array of methods available for studying reading landscape, potentially yielding more precise outcomes. Notably, eye tracking, a method that records an observer's eye movements, has gained increasing prominence. It allows for the precise tracking of an observer's gaze, facilitating detailed analysis of the areas being observed. Despite some publications delving into eye tracking research (Klein and Ettinger 2019) and exploring the relationship between eye movements and interpretation (Hu et al. 2022), these works have not been specifically focused on the landscape context (Scott et al. 2019; Hu et al. 2022). Shynu et al.'s (2021) systematic review on environmental perception encompasses a broader range of data collection methods. As the number of studies utilizing eye tracking to study reading landscape continues to grow, it becomes challenging to track the evolution of metrics, visualizations, and their appropriateness for studying reading landscape. Therefore, this review endeavors to aid researchers studying reading landscape with eye trackers by summarizing how previous studies have employed eye tracking methodology in reading landscape research.

2. Reading landscape

In the research on reading landscape, two notions are encountered whose meanings are not consistently clear: "reading landscape" and "landscape perception". While both terms broadly describe the same process, some authors interpret them more narrowly than others (see below). Bell (2001) conceptualized landscape perception as a three-step process involving the reception of visual stimuli, the intuitive recognition of aesthetic qualities, and the integration of sensory information with existing knowledge to form opinions. In contrast, Antrop and van Eetvelde (2017) delineated four primary layers of reading the landscape: scene, natural system, cultural system, and history. In this review, the term "reading landscape" is used interchangeably with "landscape perception".

The process of reading landscape can be understood through two distinct lenses: factual and aesthetic.

Factual reading landscape is grounded in observing what truly exists within it and understanding the intricate connections. This approach is heavily influenced by one's scientific perspective. Historians view the landscape as a palimpsest imbued with data from different historical eras (Cronon 2020). Geographers undertake the most comprehensive interpretation, considering the interplay between the natural and social elements of the landscape. Lewis (1979) emphasized the study of the cultural landscape, proposing seven axioms for its interpretation. These axioms encompass cultural, historical, ecological, and natural perspectives on the landscape, also integrating commonplace elements in landscape contemplation. Widgren (2004) contends that reading the landscape is an everyday human activity and forms the basis for geographical research. He also underscores the significance of human-made structures in the landscape, emphasizing the need to decipher cultural symbols and representations of cultural practices within it.

Aesthetic interpretation of a landscape is rooted in the impact of the landscape on the observer rather than the objective elements present in it. In most cases, studies utilizing this perspective aim to evaluate the visual quality of the landscape. Several models explore what renders a landscape beautiful (Tveit et al. 2006 who used the notion landscape perception) or elucidate the landscape qualities that account for inter-individual differences in its evaluation (Kaplan et al. 1989 who also used the notion landscape perception). Another concept within this perspective delves into the characteristics, knowledge, and experiences of the observer, implying that the meaning of the landscape can be interpreted differently by various observers (Duncan and Duncan 1988 who wrote about reading landscape). Despite having theoretical perspectives that explain processes linked to landscape reading, numerous questions remain unanswered. Eye tracking appears to be a highly effective tool for elucidating uncertainties in both theoretical approaches to this process. Consequently, studies based on both approaches were included in this systematic review.

3. Methods

This study conducted a review of research employing eye tracking to explore reading landscape. To make the search complete and systematic, the PRISMA statement procedure was chosen as methodological guideline, since it is recommended and accepted as a frame for writing systematic reviews (Page et al. 2021). The process commenced with the formulation of research questions stated as follows:

– Which aspects of the landscape have been studied?
– What medium is used to study reading landscape with eye tracking?
– Which visualizations of eye tracking data are used in reading landscape research?
– Which eye tracking metrics are used to study reading landscape?
– Which eye tracking metrics are used to study different aspects of landscape?
– What are the limitations of using eye tracking methodology to read landscape?

Addressing these research questions necessitated an extensive literature search. In the initial phase, titles, abstracts, and keywords of articles, reviews, and book chapters were scrutinized in two major electronic bibliographic databases: Web of Science and Scopus. The search employed the following keyword combination: ("landscape" or "urban environment" or "natural environment" or "scene perception") and ("eye tracking" or "eye tracker" or "eye movements" or "visual attention"). This choice was based on commonly used notions in the landscape reading process and eye tracking methodology, serving as criteria for article inclusion in the review. There were no restrictions on publication years or subject areas. The search encompassed articles available until December 20, 2020, and was limited to those written in English. A total of 427 records were identified in Scopus, 228 in the Web of Science database, with 161 records being duplicate for both databases. Consequently, the overall count of potentially relevant articles stood at 494 (Fig. 1).

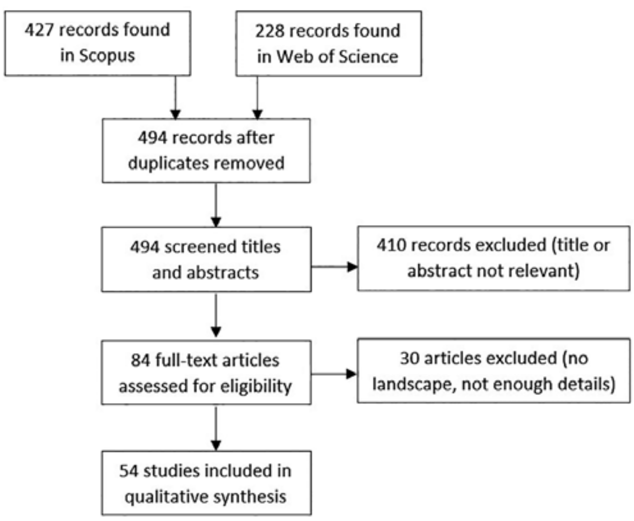

Fig. 1 Flow diagram of the literature selection process.

In the second stage, article titles were examined to evaluate their relevance. Articles completely unrelated to the topic were excluded from the analysis (e.g., neuroscience articles found in the databases that were not relevant to our objectives). A total of 273 articles were excluded based on title reading, leaving 220 abstracts for scanning in the third stage.

During the abstract analysis, it was essential to ascertain whether the study focused on reading the landscape, as defined in section 2, and if eye tracking was utilized as at least one of the methods. If this information was not evident in the abstract, the article was excluded. At this stage, 137 articles did not meet the criteria and were excluded, leaving 84 articles deemed relevant for our review. Subsequently, full-text articles were meticulously examined in the next stage.

Despite meeting our criteria, not all selected articles were utilized for the review. Some lacked pertinent information needed to address the research questions, while others were primarily oriented towards aspects like orientation, especially in flat terrain, rather than the landscape. Ultimately, 54 articles were included in the review, encompassing 56 studies (2 articles contained 2 studies).

Data from the selected studies were extracted in accordance with the research questions. The documented characteristics included the focus of the study, medium used to represent the landscape, number of participants, eye tracking metrics used and their significance, visualization of eye tracking data and its application, and results of the study. This information was recorded in a MS Excel table.

Initially, lists of topics, media, visualizations, and metrics used in the studies, along with accompanying notes, were generated. Using these lists, a summary was created. Due to the extensive variety of metrics, visualizations, and study topics, the data were coded using open coding based on grounded theory to form broader groups, aiding navigation in the lists based on identified similarities during the study readings.

Given the substantial variation in topics, an examination of the relationships between the topic and metrics employed to study it was conducted. These relationships were visualized using graph generated in SankeyMATIC application, and conclusions were drawn based on this graphical representation.

4. Results

4.1 Basic summary of the included studies

The years for potential study selection were not restricted; the earliest study included dates to 1998. Studies utilizing eye tracking methodology to

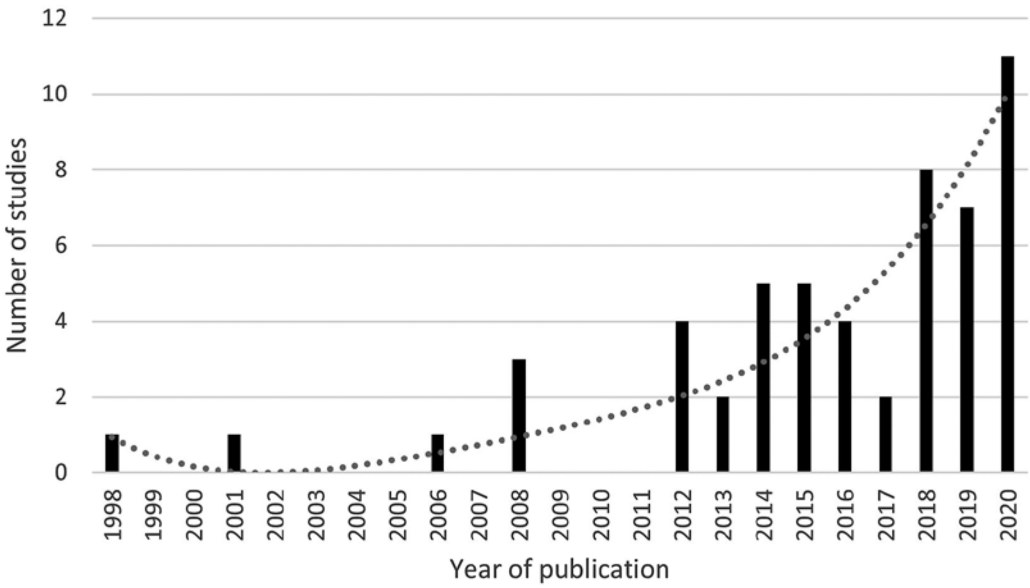

Fig. 2 Years of publication of the included studies. The trend line is a result of linear regression model and shows that number of research papers using eye tracking in landscape research has soared.

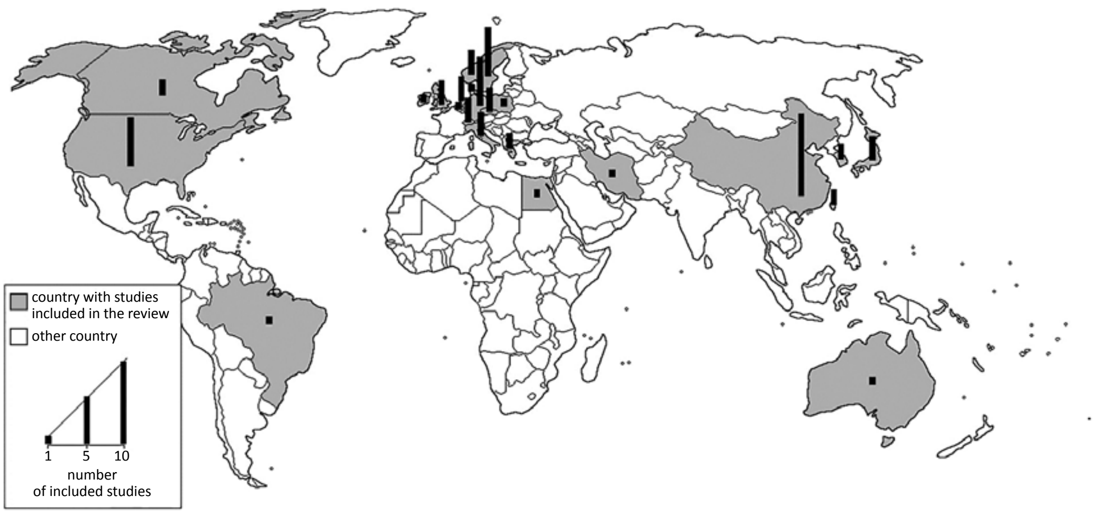

Fig. 3 The countries where studies were carried out.

investigate landscapes have been continuously conducted since 2012 (Fig. 2), demonstrating a growing trend in their number. The peak number of studies was recorded in 2020, reaching 11 studies.

Most of the studies were conducted in Europe, the second region is East Asia, with most studies conducted in China (10 studies), followed by North America. Additionally, one study each was conducted in Brazil and Australia, one study was conducted in cooperation with researchers from Egypt, and one from Iran (Fig. 3).

The number of participants in the studies varied significantly (Fig. 4). The mean number of participants was 40, with the most common range being between 26 and 50. Minimum was 3 (Nathanael et al. 2012), maximum 158 (Ren 2019).

4.2 Which aspects of the landscape are explored in the studies?

In the selected articles, a broad spectrum of study foci and aspects of landscape were observed. To address this diversity, topics and foci were coded and grouped into a more manageable set of categories. Ultimately, 8 categories were identified. It is important to note that some studies were included in multiple categories, as the categories were not initially designed to be mutually exclusive; the categorization of individual studies is shown in Tab. 1. The identified categories were as follows:

(i) **Saliency or attractiveness in the landscape** (15 studies) where parts of the landscape that attract the most attention from observers were studied.

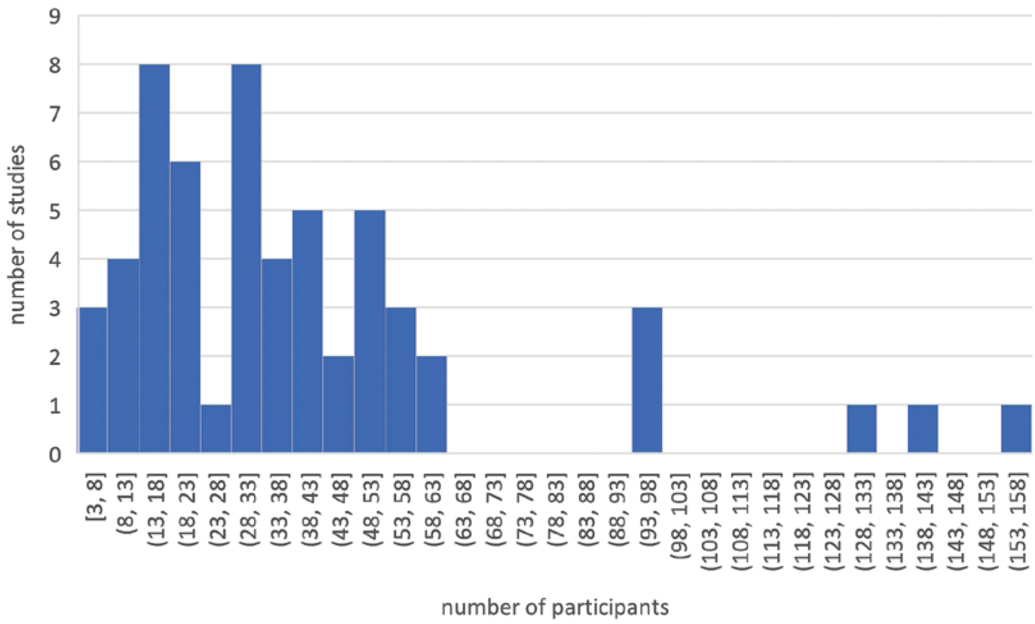

Fig. 4 Number of participants in reviewed studies.

Some also explored objects within the landscape that aid in memory recall.

(ii) **Particular type of landscape** (15 studies) focused on a specific type of landscape (e.g., pasture, forest, urban parks) and how people perceive this type of landscape. Some studies compared the perception of two different types of landscapes.

(iii) **Marketing** (8 studies) explored attractive objects/elements of landscapes to draw people's attention, often in the context of tourism (e.g., pictures in travel agency catalogs, hotel advertisements). One study focused on the effective localization and visual features of advertisements to attract the most attention.

(iv) **Restorativeness** (9 studies) investigated elements of the landscape perceived as restorative or stress-relieving, often providing recommendations for landscape designers.

(v) **Affective responses** (8 studies) focused on the positive or negative emotions and feelings people experience when observing the landscape, including differences between different types of landscapes and individual preferences for certain areas/objects within the landscape.

(vi) **Localization** (7 studies) examined map orientation and the ability of individuals to find their way or locate themselves based on a map.

(vii) **Traffic safety** (6 studies) explored the visual behavior of various traffic participants, with a primary focus on attention distribution. The studies often concluded with recommendations for urban planning and architecture.

(viii) **Other topics** (3 studies) encompassed a variety of diverse aims, including studies on the influence of sounds on reading landscape, differences in eye movements when observing static versus moving pictures, the role of text in reading landscape, and cross-cultural differences in reading landscape.

4.3 What medium is used to study reading landscape with eye tracking?

Eleven different types of media were identified in the selected studies. The most used media were various types of images, including photographs (31 studies), pictures (3), maps (1), street view (2), and aerial photographs (1). The second most frequently used medium was the real environment, where participants' eye movements were recorded in the actual landscape (15 studies). Other types of media were less commonly used and included audio-visual stimuli (2), animations (2), videos (2), a driving simulator (1), and virtual reality (1). Some studies utilized a combination of multiple media types: Kiefer et al. (2014a) used both the real environment and maps, Dong et al. (2020) combined the real environment with street view, and Hayata and Ino (1998) compared static pictures, videos, and animations.

Despite technological advancements, the presumption that static stimuli would be replaced by the natural environment, virtual reality, or videos is disproven according to our analysis. Photographs remain the most utilized medium for studying landscape reading with eye tracking. However, since 2014, when enough studies allowed for comparison, a broader range of media has been employed.

As technological advancements continue, especially with the development of mobile eye trackers, it could be anticipated that there might be a shift in the media used to study landscapes, transitioning from static pictures to dynamic media such as animations or videos, and from desktop settings to natural

Tab. 1 Classification of studies according to their topics.

Topic	Studies
Saliency or attractiveness in the landscape	Davies et al. (2006); Schumann et al. (2008); Credidio et al. (2012); Potocka (2013); Dupont et al. (2015); Pihel et al. (2015); Wang et al. (2020); Dupont and van Eetvelde (2014; 2 studies); Lin et al. (2014); Hayek et al. (2019); Spanjar and Suurenbroek (2020); Valsecchi et al. (2020); Franěk et al. (2018a); Petružálek et al. (2018); Backhaus et al. (2020)
Particular type of landscape	Nordh (2012); Potocka (2013); Nordh et al. (2013); Sang et al. (2014); Valtchanov, Ellard (2015); Cho (2016); Sang et al. (2016); Amati et al. (2018); Petružálek et al. (2018); Franěk et al. (2018a, b); Elsadek et al. (2019); Misthos et al. (2020); Zhu et al. (2020); Gao et al. (2020); Spanjar and Suurenbroek (2020)
Marketing	Takahashi et al. (2001); Potocka (2013); Li et al. (2016); Fedotov et al. (2018); Wang et al. (2018); Liu et al. (2019); Liu et al. (2020); Zhu et al. (2020)
Restorativeness	Nordh (2012); Nordh et al. (2013); Valtchanov and Ellard (2015); Amati et al. (2018); Franěk et al. (2018b); Elsadek et al. (2019); Kang and Kim (2019); Bianconi et al. (2019)
Affective responses	Liener et al. (2017); Cottet et al. (2018); Ren (2019); Stevenson et al. (2019); Gao et al. (2020); Khachatryan et al. (2020); Spanjar and Suurenbroek (2020)
Localization	Kiefer et al. (2014; 2 studies); Spiers and Maguire (2008); Emo (2012); Dong et al. (2020); Franke and Schweikart (2016); Sayegh et al. (2015)
Traffic safety	Nathanael et al. (2012); Antonson et al. (2014); Brazil et al. (2017); Stelling-Konczak et al. (2018); Dong et al. (2020); Cullen et al. (2020)
Other topics	Ren and Kang (2015; sounds); Liu et al. (2019; sounds); Hayata and Ino (1998; static vs. moving stimuli)

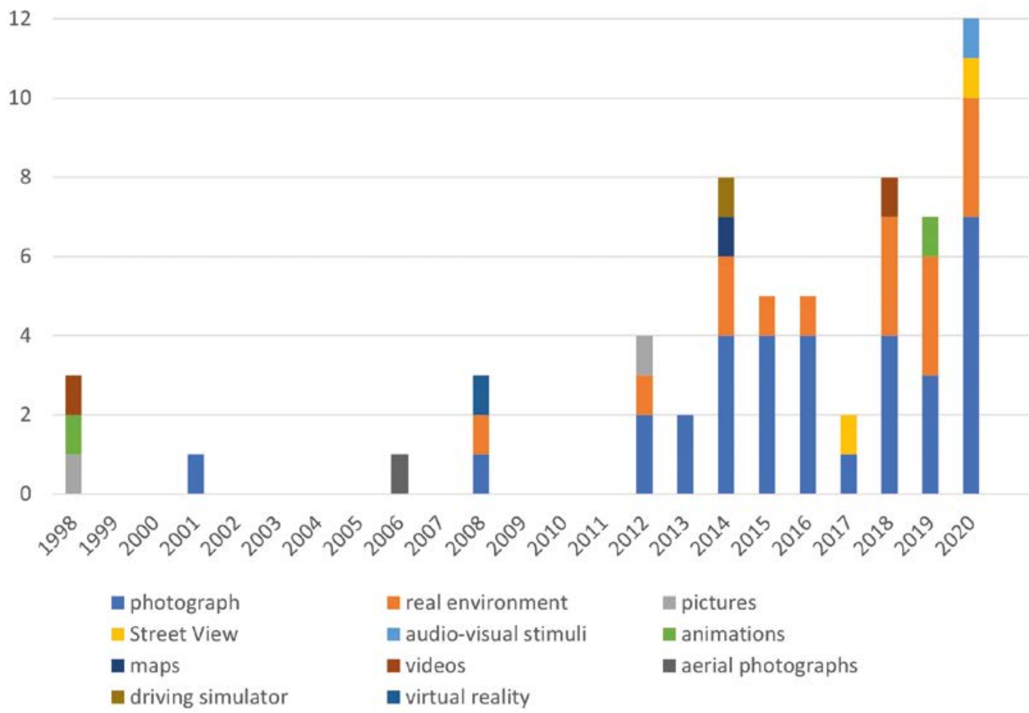

Fig. 5 Media used in the included studies according to the year of publication as they are called in the studies.

environments. Although a slight increase in the proportion of eye tracking landscape studies conducted in natural environments is observed (Fig. 5), photographs remain the most frequently used medium for this type of research, and static stimuli continue to feature prominently in most studies (Fig. 6).

4.4 Which visualizations of eye tracking data are used in landscape reading research?

In the selected studies, 14 methods of visualization of eye tracking data were identified. The most frequently used are shown in Fig. 7.

(i) **Heatmaps** (also called heat maps, attention heatmaps; 18 studies) represent the intensity of fixation in various parts of the stimulus. Heatmaps are valuable for identifying highly attended objects or symbolizing fixated areas. They are easily generated using eye tracking data processing software, and their clarity is advantageous for all readers. However, their difficult quantification is a commonly cited drawback. Heatmaps can also be employed to study different areas of the stimulus fixated by observers at various times during the observation, aiding in identifying reading strategies for the landscape (Spanjar and Suurenbroek 2020).

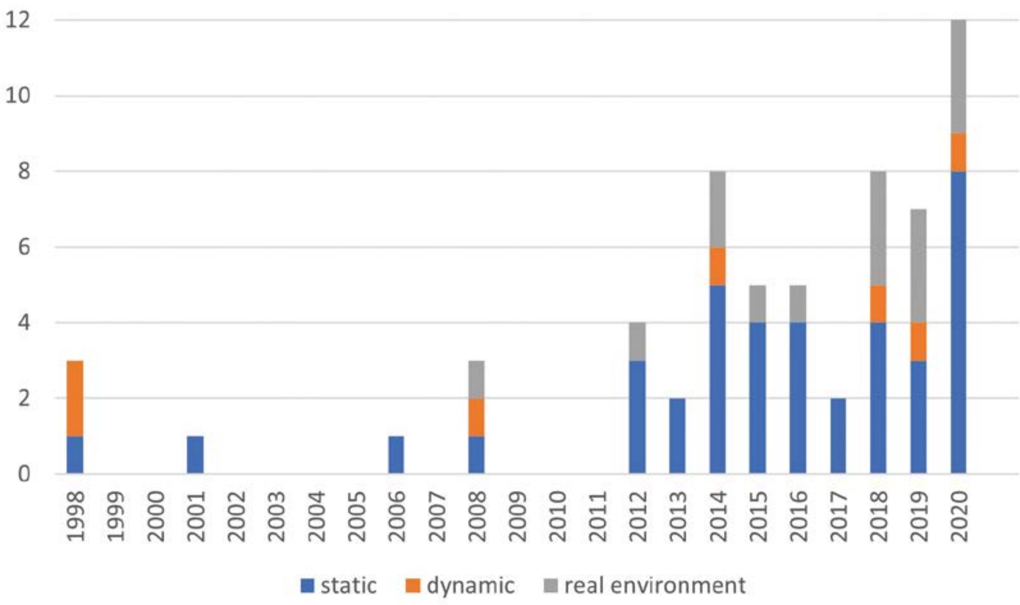

Fig. 6 Categories of media used in the included studies according to the year of publication.

(ii) **Scanpath** (also called trajectory map, gaze plot; 10 studies) is the direct visualization of eye movements. Scanpaths provide insights into the complexity and difficulty of reading the landscape.

(iii) **Luminance maps** (also called opacity maps; 4 studies) is a visualization method similar to heatmaps. Instead of color, luminance maps depict the most fixated areas of the stimulus based on opacity. Like heatmaps, luminance maps are not easily suited for quantitative research.

(iv) **Salience map** (3 studies) visualizes objects expected to naturally attract the most attention

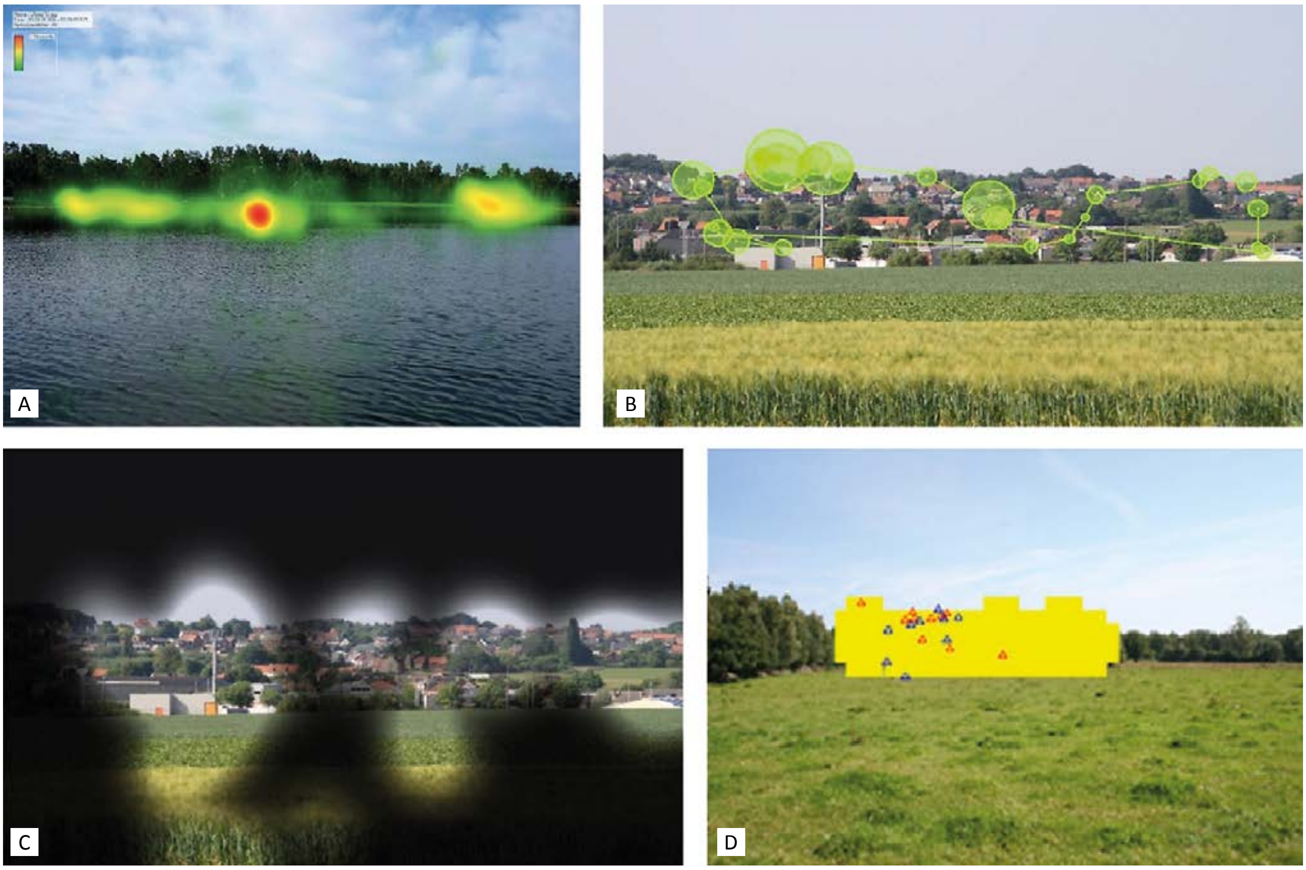

Fig. 7 The most frequently used visualizations of eye tracking/fixations data: a) heatmap (Potocka 2013), b) scanpath (Dupont and van Eetvelde 2015), c) luminance map (Dupont and van Eetvelde 2015), d) salience map (Sang et al. 2016).

Tab. 2 Overview of eye tracking metrics used to study reading landscape.

Fixations metrics	Saccades metrics	Metrics to study areas of interest	Eye characteristics	Stimulus observation characteristics
Number of fixations Fixation duration Fixation frequency Fixations per minute Fixations positions First fixation position First fixation time First fixation duration Timing of the last fixation Temporal evolution of mean fixation duration	Number of saccades Amplitude of saccades Saccades length Saccade frequency	Number of fixations in AOI Duration of fixations in AOI Number of visits in an AOI Time of the first visit in an AOI First saccade amplitude to interest area AOIs sequences	Pupil size Blink rate	Scanpath length Horizontal and vertical angle viewed Total gaze points Average nearest neighbor ratio Mean lateral visual span Mean portrait visual span Number of crossing the center line Time-course of fixations Entropy Predictability

during free viewing tasks. Identification is based on object color, intensity, and orientation. This visualization type is often used alongside heatmaps. Comparing salience maps and heatmaps can reveal the reading strategy: stimulus-driven if the maps correspond and task-driven if there are differences in visualizations. The differences can be identified by reviewing the visualizations or by examining specific objects, their salience, and fixation intensity.

(v) **Hits in cells** (1 study) is a method applicable to eye tracking without an eye tracker. The stimulus is divided into 25 cells, and after presentation, participants report the first number they see among the 25 presented (one in the center of each cell).

(vi) **Voronoi Cells** (1 study) serve to visualize the dispersion of fixations. A cell is a polygon containing all points with the lowest distance to the fixation location. Clustering of fixations results in smaller polygons.

(vii) **Boxplots** (1 study) were utilized for eye tracking analysis of video to compare the distribution of fixations between areas of interest in different landscapes. For each area of interest, boxplots were drawn and compared for both landscapes.

(viii) **Proportional graphs** (1 study) were employed to analyze the types of objects participants fixated on at different observation times. These graphs can be created for each participant to study interindividual differences or for all participants, aiding in qualitative comparison.

(ix) **Attention radius** (1 study) is the radius of the extended area resulting from the combination of all separate attention areas, which are areas with higher number of fixations in the heatmap.

(x) **Attention points** (1 study) are the numbers of separated attention areas in the heatmap.

(xi) **Total attention area** (1 study) is the area of higher attention areas in the heatmap, that are the areas for attention points.

(xii) **Fixation spatial distribution map** (1 study) is a graphical representation of fixations similar to a heatmap but also includes fixation duration. The XY axes represent coordinates from the stimulus, and the Z axis represents fixation duration. Longer fixations are represented by higher points.

(xiii) **Points in pictures** (1 study) is a method similar to the scanpath, but without the lines representing saccades; only fixations are depicted.

(xiv) **Emotions-colored cells** (1 study) is a method to visualize the emotions evoked by each object in the stimulus. The stimulus is divided into cells, each colored based on the emotion it evoked, as detected by EEG. The object's location is tracked using an eye tracker.

4.5 Which eye tracking metrics are used to study reading landscape?

There are 46 different eye tracking metrics used in 56 studies included in this review. The metrics are grouped according to the types of characteristics of eye movement into five groups: fixation metrics, saccades metrics, metrics to study areas of interest, eye characteristics metrics, and metrics of picture observation. An overview of the metrics is presented in Tab. 2.

4.5.1 Fixation metrics

Fixation metrics are crucial characteristics of eye movements extensively used to analyze reading landscapes. Fixations denote periods during which the eyes remain directed towards a single point. They are typically identified by a distance between gaze points smaller than a threshold value and a time where the participant gazes at a position for a duration exceeding the threshold. The threshold values for time varied across the included studies, ranging from 50 ms to 200 ms.

The identified metrics from the 55 studies are outlined below:

– *Number of fixations*, also known as fixation counts, number of gaze points, or total gaze points (22 studies). This metric involves counting the total number of fixations during stimulus observation and comparing them between images. A higher number of fixations might indicate less fascination with the stimulus or difficulty in observation (Berto et al. 2008; Nordh et al. 2013). Additionally, it can be interpreted in terms of stimulus memory: more fixations may imply better recall of the stimulus.

- *Fixation duration*, also called fixation time (19 studies). Mean fixation duration was utilized in 8 other studies. It measures the length of fixations and can be compared between images, participants, or participant groups. Longer fixations are associated with experts (Sang et al. 2014) and may signify a more challenging task or greater interest in the stimulus (Liu et al. 2020). Conversely, shorter fixations a more restorative landscape (Valtchanov and Ellard 2015; Kang and Kim 2019).
- *Fixation frequency* (1 study) can be interpreted similarly to fixation duration. It represents the number of fixations per unit of time.
- *Fixations per minute* were used by Stevenson et al. (2019) to account for varying walking speeds among participants in a natural environment. They found that participants exhibited a higher number of fixations per minute in a natural environment, although the precise interpretation remains unclear within the study's context.
- *Fixations positions*, also referred to as fixation locations, were widely used in the 55 studies. They are commonly employed for data visualization. Ren (2019) utilized fixation coordinates to investigate differences in assessing the tranquility of various landscape types.
- *First fixation position*, *first fixation time*, and *first fixation duration* were used to examine the most salient objects in the stimuli. First fixation position was compared to salience maps to determine whether the viewing strategy is stimulus-driven or task-driven. Sang et al. (2016) discovered that evaluating stewardship and characterizing the pasture are both task-driven. Dupont et al. (2015) discovered that the length of first fixations is higher for landscape experts than for novices. Wang et al. (2020) used first fixations as a component of a method to preserve cultural heritage. They discovered that, combined with fixation counts and previous observation length, first fixations were efficient in identifying important objects.
- *Timing of the last fixation* was used to study runners' reading of sidewalks (Cullen et al. 2020). They identified situations where participants ran towards the sidewalk curb and measured the timing of the last fixation as a percentage of the trial in which it occurred.
- *Temporal evolution of mean fixation duration* is a metric used by Franěk et al. (2018b) to examine differences in fixation durations at various times during stimulus observation. Participants watched each stimulus for 15 seconds, which was divided into three 5-second intervals, and mean fixation duration was calculated for each part. The study revealed that longer stimuli presentations correlated with longer fixations.

4.5.2 Saccades metrics

The fast eye movements between fixations are called saccades. They are supposed to not provide information about the stimulus to the observer. However, they may provide meaningful information about the strategy and the process of reading landscape. The metrics related to saccades in included studies were:

- *Number of saccades*, also called *saccades count*, counts the saccades made by an observer while viewing a stimulus. A higher count of saccades suggests a broader observation of the stimulus, contributing to a broader perception and holistic understanding of the landscape (Dupont et al. 2015). Landscape experts did more saccadic movements than laymen while observing landscape photographs.
- *Amplitude of saccades*, also called *mean exploration* measures the length of a saccade in degrees of view angle, providing insights into the main observation pattern. Smaller amplitudes, as observed in experts by Dupont et al. (2015), may indicate a more holistic and systematic perception of the stimulus. Additionally, longer amplitudes are associated with photographs that require more effort to be read (Berto et al. 2008). The amplitude of saccades depends on the task. When the task is more holistic oriented, the amplitudes are longer than by analytic oriented tasks.
- *Saccades length* is a metric similar to the amplitude of the saccades, but it is measured in pixels. It reveals valuable information about the saccade lengths. Notably, participants' saccades tend to shrink with increasing task difficulty in search tasks (Credidio et al. 2012).
- *Saccade frequency* calculates the number of saccades per unit of time. A higher frequency may indicate that the stimulus is either too simple or too complex, making it challenging for the observer to find the area of interest. Saccades were found to be less frequent when pleasant sounds or music were playing while participants read the landscape (Liu et al. 2019).

4.5.3 Metrics to study areas of interest

The stimulus could be divided into parts to better understand the way that people read the landscape. These parts are usually called areas of interest. Lin et al. (2014) used the term interest areas, Dong et al. (2020) objects of interest. There are a lot of metrics used with areas of interest:

- *Number of fixations in AOI* represents the count of fixations that the participant made in an AOI. This metric gives a basic view on objects or the parts of the stimulus that attract the most attention. People, signs, or moving objects attract most attention. But the results are influenced by the size of the areas/objects in the stimulus, so that it should be normalized by the size (Dong et al. 2020). In case of searching tasks, the AOI could be drawn around the object that should be found. The higher the number of fixations, the lower discrimination efficiency (Lin et al. 2014).

- *Duration of fixations in AOI*, also called dwell time in the AOI or time spent looking on particular object, expresses the time duration of fixations in an AOI. It is calculated as the sum of times of each fixation in the AOI. It also could be counted relatively, as a proportion of the total fixations time in the stimulus. This metric is connected to the attractivity of the parts of stimuli. In the case of search tasks, longer fixations in AOIs may signal difficulties to identify the target (Lin et al. 2014). Longer fixations in an AOI may also signalize more fascination with the AOI (Misthos et al. 2020). The experts have longer dwell times in AOIs than novices for tasks connected to biodiversity evaluation (Pihel et al. 2015). The landscape experts spend less time gazing on buildings than laymen in free viewing experiments (Dupont et al. 2015).
- *Number of visits in an AOI* is the number of fixations in the AOI that followed a fixation outside the AOI.
- *Time of the first visit in an AOI* is the time from the beginning of the experiment to the first fixation detected in the AOI. It provides information on the ability to attract attention of the AOI: Shorter times indicate higher attractiveness. The metric also depends on the position of the AOI in the stimulus: for the AOIs placed in the center or on the left side, the time is shorter than for the AOIs in the right part of the stimulus (Misthos et al. 2020). This also is valid for hazards identification by cyclists, as objects located in the center of their view attract their attention faster than the hazards on the sides, although these hazards are more dangerous (Brazil et al. 2017). An object is perceived as more disturbing, the time of the first fixation is shorter (Hayek et al. 2019).
- *First saccade amplitude to interest area* measures the amplitude of the saccade preceding the first fixation in the AOI, particularly useful in search tasks. A shorter saccade amplitude indicates increased difficulty in finding the target (Lin et al. 2014).
- *AOIs sequences* are the sequences of AOIs that were fixated in the time order in which they were fixated. They could be used to study a detailed self-localization strategy (Kiefer et al. 2014). An observer should be successful in the case he/she has the symbol/stimulus in his/her work memory, which means that the AOIs in map and in real environment should be close to each other to provide the effective information.

4.5.4 Eye characteristics

The characteristics of eyes are rarely used in the reading landscape research. There were two metrics in the studies included:

- *Pupil size*, also called *average pupil diameter*. It is related to the restorativeness of the landscape: the more restorative the landscape is, the smaller the pupil is (Nordh et al. 2013). When the stimulus is easy to perceive, the pupil is larger than in the case of difficult stimuli (Gao et al. 2020).
- *Blink rate*, which is counted as the number of blinks per minute, could be a sign of cognitive load: the number of blinks rises with cognitive load (Valtchanov, Ellard 2015). Urban scenes increased blink rates, which means they are more difficult to observe. The blink rate is also positively correlated with the number of fixations and negatively correlated with the fixation duration. The higher the blink rate, the more difficult it is to find the target.

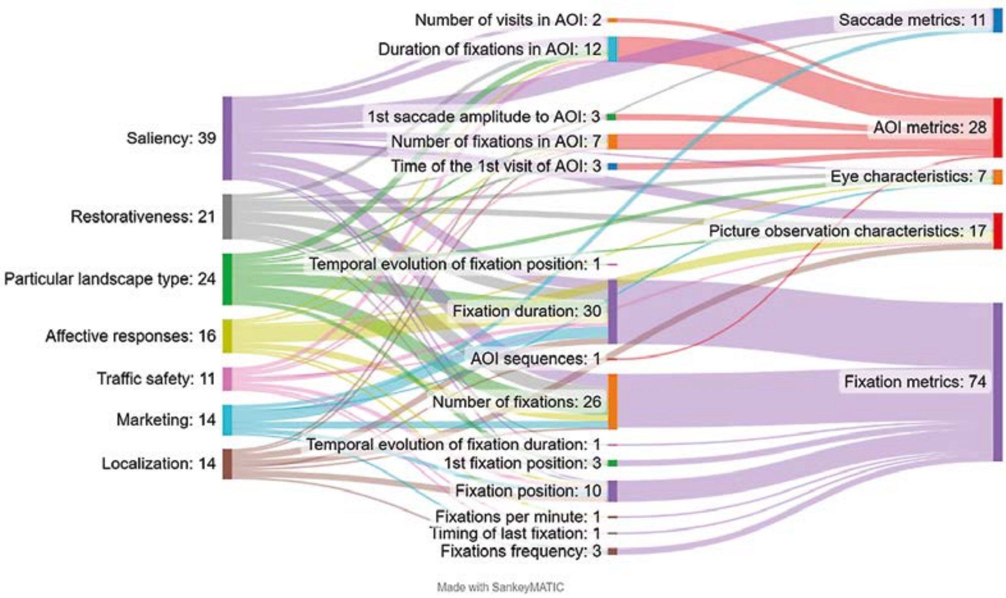

Fig. 8 Relationship of the topic of the study and metrics used.

4.5.5 Stimulus observation characteristics

There is also a wide range of metrics that provide a view on the observation of the stimulus. The metrics used in the included studies were the following:

– *Scanpath length*, also called *eye travel distance* or *former observation length* measures the length of eye movements as the gaze moves from one fixation point to another, typically measured in pixels (Kang and Kim 2019). A shorter scanpath length is associated with natural landscapes compared to built/urban landscapes, indicating a more restorative or coherent landscape (Franěk et al. 2018b). However, Valtchanov and Ellard (2015) found no significant differences in scanpath length between natural and urban landscapes, suggesting the importance of considering fixation counts alongside scanpath length. The metric could also give a rough idea about the proportion of the image that was explored when the longer scanpath corresponds with the larger proportion scanned. Landscape experts have longer scanpaths than laymen when observing landscape (Dupont et al. 2015).
– *Horizontal and vertical angle viewed* represents the range of horizontal and vertical eye movements in the stimulus.
– *Total gaze points*, also called *number of gaze points*, is the number of all points that the eye was caught during the observation. Ren and Kang (2015) and Ren (2019) used this metric, noting variations in gaze points with different landscape types and tasks. For instance, fewer gaze points were observed when assessing visual aesthetic quality compared to tranquility. However, the number of gaze points was not significantly influenced by the type of landscape (Ren 2019).
– *Average nearest neighbor ratio* is a GIS measure that quantifies the spatial distribution of points, where a lower value indicates more clustered points. Dong et al. (2020) utilized this to study stimulus exploration, finding fixations to be more clustered in a real environment compared to a desktop environment during a self-localization task.
– *Mean lateral visual span* represents the effective visual range horizontally and vertically, respectively, while participants gaze at a stimulus (Gao et al. 2020). The higher the satisfaction is, the smaller the mean lateral visual span.
– *Mean portrait visual span* is the effective visual range obtained by participants gazing vertically at a stimulus and the usage and the meaning are the same as the mean lateral visual span (Gao et al. 2020).
– *Number of crossing the center line* is useful when observers need to choose between two variants in the stimulus, such as selecting the left or right street at a crossroads (Emo 2012), indicating the difficulty of making choices.
– *Time-course of fixations* was utilized to study whether participants look at a selected road first, for longer durations, or repeatedly in tasks like choosing a route at crossroads (Emo 2012).
– *Entropy* could be used to characterize the degree of uniformity of a distribution of fixation locations (Backhaus et al. 2020). It varies with the task, being higher for guess tasks, indicating a more even distribution of fixations, and is influenced by what needs to be counted in the picture.
– *Predictability* is the function that can be used to investigate how well an empirically observed fixation density or the fixation density generated by a computational model predicts a set of fixation locations (Backhaus et al. 2020). It is also a task-dependent metric.

4.6 Which eye tracking metrics are used to study different aspects of landscape?

In the initial analysis, metric groups for different topics were examined. Fixation metrics, being the most universally used, were employed across all topic groups. Metrics related to picture observation characteristics and AOIs were utilized in all groups except for marketing studies. Interestingly, in saliency studies, AOIs and fixation metrics were nearly equally prevalent. Saccades metrics were utilized for only two topics: marketing and saliency (Fig. 8).

Among fixation metrics, fixation duration was the most frequently employed metric across all topics (Fig. 8). Except for studies focused on a particular type of landscape (where fixation position was not used) and studies centered on traffic safety (where fixation duration was not used), both fixation position and number of fixations were commonly used across almost all topics. For the traffic safety studies, there were notable differences in fixation metrics and their structure.

In the realm of AOIs metrics, the duration of fixations in AOIs emerged as the most commonly used metric across all but one topic (Fig. 8). The exception was marketing studies, for which no AOIs metrics were utilized. The number of fixations in AOIs was also frequently employed for five topics, excluding marketing and restorativeness. AOI metrics were predominantly employed for studying saliency and particular landscape types. In the case of saliency, there was a diverse range of metrics (five different types, most of them used more than once).

4.7 What are the limitations of using the eye tracking methodology to read landscape?

The eye tracking methodology has introduced new avenues for studying visual attention towards landscapes; however, it also harbors several limitations. Firstly, it is linked to the eye-mind hypothesis, assuming no delay between fixation and processing (Just and Carpenter 1980). The validity of the eye tracking methodology hinges on accepting this hypothesis.

Physiological measures are less sensitive than cognitive measures, posing challenges, especially in studying restorativeness (Nordh et al. 2013). Eye movement data can be affected by motion sickness and visual fatigue. Sang et al. (2014) highlighted that relying solely on heatmaps or first fixation measures is not precise enough for studying reading landscape. Liu et al. (2019) even emphasized the need for additional measures such as EEG or electrodermal activity for a more precise understanding of perception. Another potential issue stems from the risk of movements in infrared reflection lenses, which can disrupt calibration (Cullen et al. 2020). Eye trackers can pinpoint where attention is directed, but not explain the cognitive processes behind it (Lappi 2015). Moving objects often draw attention, irrespective of their other qualities, posing challenges for eye tracking data analyses (Dong et al. 2020).

Furthermore, there are limitations related to laboratory eye tracking experiments. Many authors have cited the restricted field of view (e.g., Schumann et al. 2008; Lappi 2015), which could mean a lack of peripheral object information (Stelling-Konczak et al. 2018) and most fixations being near the center of the picture (Brazil et al. 2017). Focusing solely on eye-in-head movements overlooks head movements. In numerous cases, head movements, a vital aspect of visual attention study, cannot be measured by an eye-tracker (Schumann et al. 2008), and the perception is a passive, not active process (Berto et al. 2008). Participants can't move in a typical laboratory setting, creating difficulties in generalizing research results to real environments where individuals change positions (Dong et al., 2020) or need to navigate around other people to prevent collisions (Franke and Schweikart 2016). The limitation also extends to the tasks given by instruction in a laboratory environment, which aren't naturalistic (Lappi 2015).

Other limitations are tied to using eye trackers in real environments. Real-life situations are exceedingly complex and continuously changing, making it challenging to compare different participants observing different landscapes (Spanjar and Suurenbroek 2020). The accuracy of mobile eye trackers is lower compared to laboratory eye trackers, partly due to infrared radiation from the Sun disrupting infrared eye trackers (Lappi 2015). Processing data from mobile eye trackers, particularly when participants move during the experiment, is time-consuming, leading to a smaller number of participants in studies (Cottet et al. 2018).

5. Discussion

The objective of this systematic review was to aid researchers studying reading landscape with eye trackers by summarizing how previous studies have employed eye tracking methodology in reading landscape research. The findings revealed a noticeable increase in the number of such studies since 2012, mirroring trends observed in research on other phenomena utilizing eye tracking methodology (Borozan et al. 2022 in a study of financial decision making; Blascheck et al. 2017). These studies have primarily been conducted in Europe, North America, and East Asia, with at least one study conducted on each continent, aligning with patterns observed in eye tracking studies on financial decision making (Borozan et al. 2022). The average number of research participants was 40, with a relatively large variance, consistent with eye tracking studies in various fields (Strzelecki 2020; Deng and Gao 2022).

Despite the rapid advancement of digital technology and mobile eye trackers, the most utilized medium continues to be the photograph, typically presented on a computer screen. This preference likely stems from the necessity to acquire high-quality data, as computer-connected eye trackers still offer greater accuracy than their mobile counterparts. However, in comparison to other research domains, real-world experiments are more prevalent in landscape reading studies (Blascheck et al. 2017; Shynu et al. 2021; Borozan et al. 2022; Ke et al. 2024).

The most commonly utilized visualizations of eye tracking data in landscape reading are heatmaps and scanpaths, although accurately evaluating and comparing them can be quite challenging. However, heatmaps are relatively straightforward to read and interpret. This trend is consistent with other topics investigated using eye tracking methodologies (Raptis et al. 2016; Scott et al. 2019; Strzelecki 2020). However, in the realm of landscape reading, there exists a greater diversity in visualization methods. Despite this, several potentially beneficial data visualization methods remain untapped in landscape reading research (Blascheck et al. 2017).

Within landscape reading studies, the metrics employed exhibit greater diversity compared to other areas of eye tracking research, but the most frequently utilized metrics remain consistent: primarily, these involve the number or duration of fixations, followed by saccade metrics (Raptis et al. 2016; Scott et al. 2019; Strzelecki 2020; Ke et al. 2024). Characteristics of eyes are less commonly employed. The use of AOIs, which is typical in landscape reading studies, is absent in research on certain other phenomena (Strzelecki 2020; Ke et al. 2024). While the interpretation of metrics generally aligns (such as cognitive demand for fixation duration or pupil size (Ke et al. 2024)), differing interpretations of some metrics are not uncommon (for instance, a higher number of fixations may indicate greater cognitive demand, but also higher salience of the region in the context of video-based learning studies (Deng and Gao 2022), and reduced engagement with the stimulus in the case of landscape reading). Several metrics have rather specific interpretations in the context of landscape reading, particularly concerning restorativeness.

The studies included in this review agree that eye tracking has great potential in studying various aspects of landscape reading. It is the second most commonly used method in the study of environmental perception (after EEG, Shynu et al. 2021). The method also appears to be suitable for studying a number of other topics (e.g., Borozan et al. 2022).

5.1 Future directions

Based on the insights from the reviewed studies, several recommendations for future research can be proposed. Firstly, authors are encouraged to provide a more precise description of the eye tracking metrics utilized in their research – the definitions should be more comprehensive to enable readers understand, imagine, calculate and apply the metrics in future research. It should be clarified whether the metric is calculated individually for each participant or collectively for all participants. Authors should also specify whether they calculate the metric from all fixations coordinates or from a specific range within a heatmap. This will enhance reader comprehension and facilitate the assessment of study validity. Secondly, the selection process of participants and their backgrounds should be comprehensively described in each study, to enable readers to evaluate potential generalizability of research outcomes.

Thirdly, there is a need to develop a robust method for the precise analysis of heatmaps, given their frequent use for data visualization and interpretation. Current practices may not fully exploit their potential validity, and leveraging artificial intelligence could significantly enhance the accuracy of heatmap analysis.

Considering the limitations associated with laboratory eye tracking experiments and their potential lack of generalizability to real-life situations, a greater emphasis on conducting eye tracking experiments in real environments is advised. In these settings, a more realistic representation of visual attention may be provided. Progress has been made in analyzing mobile eye-tracker data, leading to increased efficiency, reduced time costs, and improved accuracy (Hooge et al. 2024), thereby enhancing the potential for conducting eye tracking research in real environments. Pervasive gaze sensing technology could potentially be utilized for research in real environments, as it can monitor people's gaze without their knowledge (Valsecchi and Codispoti 2022), thus mitigating the risk of Hawthorne effect potentially occurring during eye-tracking experiments (Worthy et al. 2024).

Another method to address the limitations of laboratory environments is the adoption of webcam-based eye tracking, which has shown increasing accuracy (Kaduk et al. 2023; Saxena et al. 2023). This approach may rely e.g. on computer vision and deep learning techniques (Saxena et al. 2023). With webcam-based eye tracking experiments, participants can remain at home, utilizing their own laptops. Research has demonstrated that employing this form of eye tracking, as opposed to infrared eye trackers, does not significantly affect the outcomes of certain psychological studies (Bogdan et al. 2024). Furthermore, many reviewed studies focused on participant observation without specific tasks, leading to stimulus-driven results. Exploring task-driven perception of landscapes and discerning the strategies employed by different groups of people for varied tasks in the landscape would be intriguing and enrich our understanding. It has been demonstrated that various tasks exert a significant influence on eye movements (Marconi et al. 2023).

Lastly, with the rapid advancements in artificial intelligence, novel methods emulating eye tracking have emerged (e.g., 3M VAS). Future research could delve into understanding how assumptions made by artificial models differ from the perception of diverse groups, such as novices and experts. Notably, significant differences in eye movements have been observed among these groups during landscape observation, warranting a deeper exploration of these disparities.

6. Conclusions

The number of studies focusing on landscape reading utilizing eye tracking methodology has been steadily increasing. Consequently, a systematic review summarizing the methodologies employed in this research was undertaken. The research was primarily conducted in three regions: Europe, North America, and East Asia. A diverse array of media was employed to visualize the landscape. Despite the growing accessibility of mobile eye trackers, photographs remain the predominant choice. Heatmaps and scanpaths emerged as the most frequently used methods for visualizing data, with fixation metrics being the predominant choice in landscape reading research. In the case of saliency studies, metrics of AOIs were utilized just as frequently as fixation metrics.

This review offers a comprehensive overview of the metrics and visualizations associated with eye tracking data in landscape reading research, accompanied by explanations and possible interpretations. As a result, this review stands to be invaluable for researchers in this field, providing reassurance and guidance for their ongoing or future research endeavors. Moreover, journal article reviewers will find this overview exhaustive and informative, aiding them in assessing the accuracy and benefits of new research.

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