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Eye-tracking study of generation z's visual attention to traffic signs

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ABSTRACT
The number of accidents in Indonesia reached 116 thousand cases in 2023, including in University areas. Most of the traffic victims are Generation Z. The impact of road accidents includes minor injuries, serious injuries, deaths, and material losses. In order to achieve the golden generation in 2045, Generation Z can achieve driving safety on the highway by ensuring a level of understanding of the meaning of traffic signs to drive safely. The purpose of this study is to investigate the visual search pattern of Generation Z on traffic sign design using an ergonomic approach. This study uses an experiment with three conditions, namely displaying warning signs, prohibitions. The results showed that the values of blink duration, dwell time, and total fixation duration did not have significantly different values for each sign condition, but the blink frequency values for the three sign conditions had significantly different values. As many as 91% of the gaze map direction moves from the top left to the center of the traffic sign. Counseling through interactive visual media will be more effective and appropriate for Generation Z. This results could help government and the National Police of Indonesia to minimize the risk of accidents.

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1. INTRODUCTION

The number of accidents in Indonesia reached 116 thousand cases, including in the road area around the university [1]. Most traffic victims are in the productive age range, including Generation Z (Born in 1997-2012), who in 2024 were age 17 -27 [2]–[6]. The impact of accidents on the highway included minor injuries, serious injuries, deaths, and material losses recorded 280 million Rupiah [7]. The causes of road accidents include human factors, vehicles, and the road environment [8]–[11]. Each factor has an important role and is interrelated with the others. For example, for the case of an accident on the road that was initiated because there was an issue of traffic violations [12]. Driving safety on the highway will be achieved if every road user understands the meaning of the existing traffic rules, especially in the form of traffic signs and driving safely. Almost all existing highways have been installed with various kinds of traffic signs, including in the highway area around the university, but accidents still occur. For example, violations include exceeding the speed limit, not using helmets or seat belts, and not heeding other traffic signs. In addition, traffic violations can also disrupt the overall flow of traffic, causing confusion and congestion on the road [13], [14]. Several studies abroad have tried to measure driver behavior in processing information in traffic signs by using several measurements of cognitive visual aspects, such as eye movement patterns and areas of interest [15]–[17]. However, differences in the characteristics of traffic signs' appearance, the behavior of Generation Z drivers, and the unique condition of highways in Indonesia need to be further researched, especially in the highway area around universities and offices. University and office environments are critical areas because they represent high-traffic zones with a high density of Generation Z road users, who are university students and was involved the accident [18]–[20].

The number of Generation Z people who use driving on the highway was increase. In addition, this research is expected to support the government's program in improving the best Traffic and Road Transport Safety (KLLAJ) in Southeast Asia through the Creation of Sustainable Systems, Strengthening Coordination, and Development of Information and Communication Technology (RUNK LLAJ 2021-2024) especially for Generation Z [21], [22]. The results of this study can also be helpful for the Directorate General of the Ministry of Land Transportation and the Indonesian National Police in designing mitigation strategies in the form of developing traffic sign visualization to minimize accidents on the highway. Visual search patterns are the process of retrieving information received by the eye, which is then processed and interpreted cognitively by humans [23], [24]. This search pattern will have an impact on the actions or responses given by humans. Factors that can affect visual search in humans include attention, eye movement patterns, search patterns based on specific goals [25]–[28]. The condition of these factors in the driver can be measured using eye tracker technology in laboratory-scale measurements.

Several studies have objectively measured visual search patterns on traffic signs for drivers using approaches such as heatmaps, area of interest (AOI), gaze points, eye movement, and pupil diameter [12], [15], [17], [29]. The tools used to detect visual search patterns include various types of eye tracker equipment that can be installed on the participant's head and attached to the computer, as well as eye trackers that are installed separately with the computer, starting from various brands, namely Tobii, Gaze Point, Pupil Labs, and EyeTech Digital Systems [30]–[32]. Previous research utilized Tobii eye trackers, selected for their high resolution and real-time data generation capabilities, which are essential for laboratory-scale observation [32]. In addition, previous research has measured the level of human understanding of signs subjectively [33]. Another study showed that visual ergonomics approached can analyzed the physical detectability of traffic signs using fixation-based metrics (heatmaps) [34]. Cognitive ergonomics is also applied to assess cognitive workload by interpreting the meaning of sign measured by blink frequency an duration [35]–[37]. However, the use of objective and subjective methods together can help us understand drivers' visual search patterns and minimize the risk of accidents on the road.

Based on the previous explanation, this study aims to investigate the visual search patterns and heat maps of Generation Z in traffic sign design using an ergonomic approach (both visual and cognitive ergonomics) and eye tracking technology. The empirical insights generated from this research are strategically intended to assist regulatory authorities, such as the Directorate General of Land Transportation and the National Police of the Republic of Indonesia, in developing targeted interventions to mitigate traffic risks and minimize collision rates on highways, particularly within high-density institutional zones such as university campuses and commercial office districts.

2. MATERIALS AND METHODS

The research will be carried out using data collection and laboratory experiments at the Work System Design and Ergonomics Laboratory, Institut Teknologi Sumatera. The stages of this research consist of a pilot test stage and a data collection stage.

2.1. Participants

The participants of this study are motorcycle or car drivers, with a total of 13 people consisting of participants who can drive motorcycles and cars. The criteria for participants in this study were Generation Z drivers who actively drive and are active college students. The driving experience metrics were captured via self-reported questionnaires, reflecting the practical duration of vehicle operation. In the local socio-cultural context, it is common for individuals to gain informal driving experience during early adolescence prior to reaching the legal driving age of 17. In addition, the participants also did not have sleep problems, participants were required to have at least 8 hours of sleep the night before the experiment, did not consuming caffeine or energy drinks the day before experiment, participant in good health, and did not have a history of chronic diseases. Participants will be given a questionnaire for health condition examination based on the condition of the last 1 year to determine eligibility as a research participant. A total of 1 research participant took part in the pilot test, and 12 other people took part in the data collection process.

2.2. Experimental Design

The data collection process using three experiment conditions were actually carried out using a within-subject design for 12 people [38], [39]. Meanwhile, Each research participant will be given a display of 21 traffic sign designs with the purpose of warnings (7 signs), prohibitions (7 signs), and instructions (7 signs). To prevent order effects and fatigue, the sequence of the traffic signs was randomized for each participant. Each stimulus was displayed for 15 seconds, followed by white blank screen featuring a fixation cross to reset the gaze point before the next stimulus appeared. The Complete setup and environment during this data collection process are representatively illustrated in Figure 1.

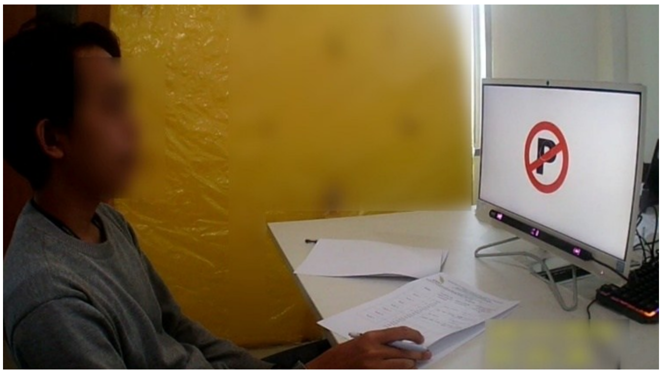

Figure 1. Experimental setup and apparatus configuration for eye-tracking data collection

2.3. Procedures

The pilot test stage aims to ensure that the research procedures to be carried out are in accordance with ethics and ergonomic research principles. The experimental procedure began with a preliminary field observation conducted around the university campus zone to ensure ecological validity. Based on these observed real-world conditions, 21 representatitive traffic signs were selected as the experimental stimuli. Subsequently, a pilot test involving one participant 1 was conducted using three experimental conditions and using an eye tracker (Tobii, Sweden) in accordance with the flow of research procedures in the data collection process to validate the experimental conditions and the stability of research procedure. At the pilot test stage and actual data collection, each research participant was asked to fill out a consent form containing an explanation of the confidentiality of the research and research procedures. After that, participants filled out a research demographic questionnaire and continued by conducting a laboratory experiment process by staring at a computer screen that was equipped with an eye tracker. The computer screen display presented three types of traffic sign conditions with the help of Microsoft PowerPoint. All traffic signs displayed are selected based on the traffic signs that are most commonly found in university or office highway areas [40].

2.4. Experimental Variables

To systematically evaluate the driver visual behavior and cognitive ergonomic responses of Generation Z, the experimental framework was structured around a well-defined set of variables. The primary Independent Variable (IV) was established as the Traffic Sign Type, which is a categorical factor consisting of three functional levels, namely Warning signs, Prohibition signs, and Instruction signs. Concurrently, to capture comprehensive physiological and spatial visual search patterns, several Dependent Variables (DVs) were evaluated via eye-tracking instrumentation. These dependent metrics comprised four temporal attributes, which included Blink Duration defined as the mean time taken to complete a single blink cycle, Total Fixation Duration representing the cumulative time spent maintaining focal attention within the designated Area of Interest (AOI), Dwell Time measuring the total duration of a visit within the AOI encompassing all fixations and saccades, and Blink Frequency capturing the total count of blinking episodes during stimulus exposure. Additionally, two spatial dependent variables were tracked, consisting of the Initial

Saccade Trajectory to evaluate the percentage of spatial direction of the primary eye movement vector (classified into upper-left to center versus upper-right to center) and the Focal Heat Map Allocations to qualitatively analyze the spatial density and distribution of visual fixations relative to specific sign elements such as symbols versus alphanumeric text.

2.5. Data Analysis

The data processing integrates visual and cognitive ergonomics with two stage information processing framework. Visual ergonomics constitutes the initial stage, emphasizing the physical detection or attention of traffic sign features such as shapes, colors, and symbols, assessed through gaze patterns and heatmaps. In the subsequent stage, cognitive ergonomics analyses the translation of these visual stimuli into decisions, measured by dwell time and total fixation duration [41]. Besides that, cognitive workload was assessed using both blink duration and frequency [35]–[37]. While visual ergonomics addresses detectability, cognitive ergonomics is essential for accident mitigation because it reflects the driver's cognitive workload and interpretation. This dual approach establishes an objective, real-time connection between visual search and decision-making, thereby distinguishing it from traditional situational awareness research. The results of this study are in the form of an area of interest for the participants, such as the display of traffic signs with warnings, prohibitions, and instructions. In the next step, data processing of eye movement patterns, heat maps, processing time and blinks was carried out for each condition of the study and participants. The data processing process uses video data extraction and data recapitulation in Microsoft Excel and area of interest analysis as the research output of 3 laboratory experiment conditions based on screen recordings and data from the eye tracker. The inferential statistical analysis was initiated by employing the non-parametric Kruskal-Wallis test to evaluate all eye-tracking metrics specifically blink duration, dwell time, total fixation duration, and blink frequency across the three functional traffic sign conditions (Warning, Prohibition, and Instruction). Subsequently, post-hoc pairwise comparisons were executed using the Mann-Whitney U test, with all computational procedures processed via Minitab software. In addition, a descriptive and qualitative statistical analysis process was carried out on the results of the questionnaire on the level of understanding of research participants.

3. RESULTS

The results of this study consist of participants demographic data, respons time, heatmaps, eye gaze, and eye blinked data. All over data was processing based on 12 participants with 3 types traffic signs condition of experimental such as condition 1 (warning signs), condition 2 (prohibitions signs), contidion 3 (instruction signs).

3.1. Demographics

The participans's demographic data consisted of 12 individual from Generation Z. In this study, participants's age ranged from 20 to 23 years (*M*= 21.5, *SD*=0.9). The group comprised with four female participants and eight male participants. All participants were active university students with a valid driver's licence (SIM A/C) and at least 3 years of driving experience. The participants had an average driving experience of 6 years (*M*= 6.3, *SD*=2.4). The usual transmission type was manual (5 participants) and automatic (7 participants), with vehicle production dates ranging from 2007-2023.

3.2. Visual Search Analysis

The following is a recapitulation of the results of data processing from 12 participants. The data processed included blink frequency, blink duration, total fixation duration, and dwell time. The results of data processing can be seen in Table 1. The eye-tracking data collected from 12 participants were evaluated using the non-parametric Kruskal-Wallis test across 252 comprehensive observations (84 observations per sign type), as presented in Table 1. The global statistical analysis revealed that the temporal metrics of Blink Duration ($H(2) = 0.47$, $p = 0.790$), Total Fixation Duration ($H(2) = 2.83$, $p = 0.243$), and Dwell Time ($H(2) = 0.28$, $p = 0.868$) did not exhibit statistically significant differences among the three functional categories (Prohibition, Warning, and Instruction signs). This statistical uniformity suggests that the microscopic cognitive processing speeds and focal extraction times of Gen Z drivers remain relatively stable regardless of the physical layout variations across the different sign categories.

Table 1. Non-parametric of gen z's visual search analysis based on traffic sign category

Eye-Tracking Metric	Traffic Sign Type	N	Median	Mean Rank	DF	H-Value	*P-Value*
Blink Frequency *(blink/min)*	Prohibition	84	3	113.2	2	15	**0.001***
	Warning	84	4	151.3			
	Instruction	84	3	115			
Blink Duration *(ms)*	Prohibition	84	121.02	128.2	2	0.47	0.79
	Warning	84	129.71	122.1			
	Instruction	84	137.1	129.3			
Total Fixation Duration *(s)*	Prohibition	84	9	129.3	2	2.83	0.243
	Warning	84	9	134.1			
	Instruction	84	8.5	116.1			
Dwell Time *(s)*	Prohibition	84	9.5	123.6	2	0.28	0.868
	Warning	84	10	129.5			
	Instruction	84	10	126.4			

Note: DF = Degrees of Freedom; H-Value represents the Kruskal-Wallis test statistic adjusted for ties.
**Statistically significant at the α= 0.05 level.*

Conversely, a highly significant difference was observed for Blink Frequency across the traffic sign conditions (H(2) = 15.00, p = 0.001). This global significance was clearly driven by the structural shift in the data distribution, where Warning signs elicited a notably higher median blink frequency (Median = 4.00) and a higher mean rank (151.3) compared to both Prohibition signs (Median = 3.00, Mean Rank = 113.2) and Instruction signs (Median = 3.00, Mean Rank = 115.0). To further examine the significant differences observed in the Blink Frequency metric, pairwise post-hoc comparisons were carried out using the Mann-Whitney U test, as presented in Table 2.

Table 2. Post-hoc pairwise comparisons using mann-whitney u test for blink frequency

Metric	Traffic Sign Type	*P-value*	Significance
Blink Frequency	Prohibition vs. Instruction	0.467	Non-significant
	Prohibition vs. Warning	0.063	Marginally significant
	Warning vs. Instruction	0.467	Non-significant

Note: Pairwise comparisons evaluated against the standard significance level of α= 0.05.

As detailed in Table 2, the pairwise analyses revealed that strict statistical significance was not achieved across the functional pairs when compared against the standard alpha threshold (α= 0.05). Specifically, the comparisons of Prohibition versus Instruction signs and Warning versus Instruction signs both yielded identical non-significant results (p = 0.467, which is well above α = 0.05. However, when evaluated against this benchmark, a prominent marginal trend towards significance was identified exclusively between Prohibition and Warning signs (P = 0.063). Although this value slightly exceeds the strict α = 0.05 criterion, the marginal variance strongly indicates that the shift in physiological demand and visual attentiveness among Gen Z drivers is most pronounced when transitioning between restrictive (Prohibition) and preventative/hazard-based (Warning) visual stimuli, rather than when interacting with informational guidance (Instruction).

3.3. Visual Gaze and Heat Map Analysis

Regarding the spatial gaze metrics, the analysis of 252 gaze snapshots revealed distinct visual scanning strategies among the Gen Z participants. The overall gaze patterns showed that 91% of eye movements were directed from the upper left quadrant toward the center of the traffic signs, while the remaining 9% moved from the upper right to the center as representatively illustrated in Figure 2. Furthermore, the heat map analysis uncovered variations in focal strategies across sign categories. For warning signs, participants' visual attention was predominantly focused on the core symbolic objects rather than the complementary borders or framing lines. For prohibition signs, attention was heavily centered on the alphanumeric characters, primarily targeting the first and second letters when multi-letter elements were present. Lastly, for instruction signs, participants prioritized processing the symbolic graphic objects over background lines or supplementary text elements.

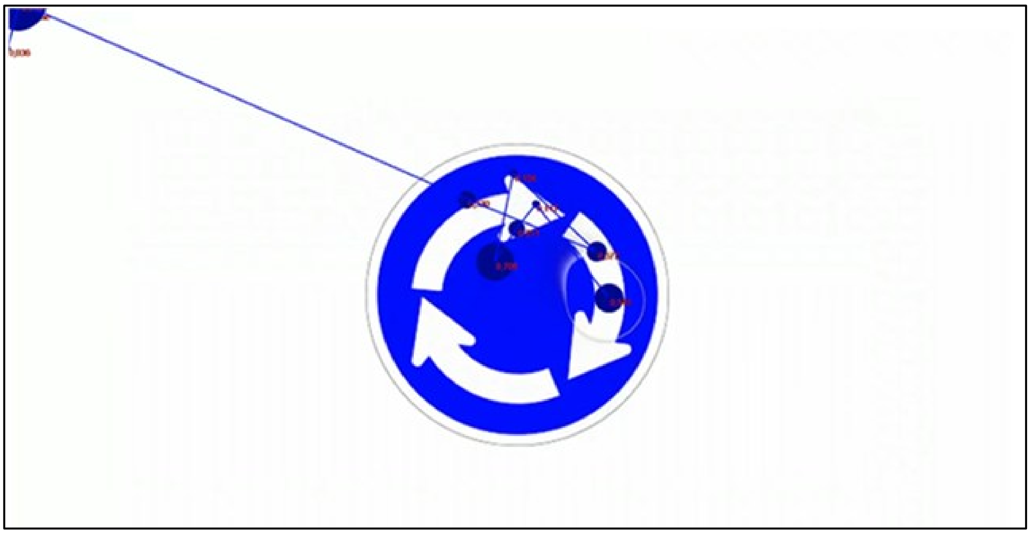

Figure 2. Representative gaze plot illustrating the dominant visual scanning pathway from the upper

4. DISCUSSION

The experimental findings regarding the rapid processing speed across sign conditions align with existing literature suggesting that Generation Z often exhibits highly developed visual-perceptual tendencies, largely shaped by their immersive exposure to digital environments from an early age [42]. Although this study focuses exclusively on characterizing Gen Z's internal visual search mechanics without a direct comparative generational control group, the observed efficiencies in symbolic processing and systematic saccade pathways indicate a strong baseline capacity for managing dense visual stimuli. The findings of this study showed that participants tended to focus on key visual elements such as symbols on warning signs or initial letters on prohibition signs. This reflects a deeply ingrained preference among Generation Z for glance-based visual information, leading them to intuitively anchor their attention on easily recognizable icons. In addition, Generation Z often engages in multitasking, such as driving while playing music or using navigation devices. The attention patterns detected in the study, such as movement from top left to center, suggest that Generation Z tends to rely on more directed and trained visual attention patterns to absorb important information quickly. Multitasking activities can limit the duration of their focus on the signs, so visual elements must be able to convey messages efficiently. This is in line with studies [43], [44], which demonstrate that minimalist but informative visual design is more effective in conveying information.

When examining the physiological response through Blink Frequency, the global analysis indicated an overall distributional shift across sign types, driven predominantly by a prominent marginal trend between Prohibition and Warning signs (p = 0.063). Descriptive metrics support this directional shift, with Warning signs eliciting a higher median blink frequency (Median = 4.00) compared to both Prohibition and Instruction signs (Median = 3.00). In cognitive ergonomics, an elevated blink frequency is closely linked to heightened cognitive workload, informational ambiguity, or transitional visual search patterns rather than generic visual fatigue.

Because Gen Z drivers are heavily habituated to high-stimulation digital environments, their visual sampling rate increases when encountering warning configurations that require immediate hazard appraisal. This subtle physiological divergence suggests that warning layouts trigger more complex internal processing or validation verification before driving decisions are made [45]. Therefore, optimal signage design must ensure that high-priority warnings are highly conspicuous to prevent critical information loss during blinking episodes [46]. Furthermore, as demonstrated by the heat map results, Gen Z individuals displayed a clear visual preference for symbolic graphics over alphanumeric text on warning and instruction signs. This behavioral trait reflects their modern reliance on immediate, glance-based iconography, aligning with prior literature Lo et al. [47] which asserts that universal symbols optimize structural visual interpretation efficiency under time-constrained tasks such as driving.

Given that Generation Z represents a significant cohort of current and future road users, the approach to driver education and highway safety campaigns must be adaptively adjusted to leverage their specific visual tendencies. Counseling and training programs utilizing interactive visual media, such as virtual reality simulations or concise, high-impact video formats could prove far more effective than conventional, text-heavy methods. Furthermore, these findings provide critical insights for transport authorities, suggesting that future traffic sign designs must become more inclusive of this generation's distinct visual behaviors. Future research should also explore how emerging technologies, such as Augmented Reality (AR) heads-up displays, can be integrated to enhance real-time engagement and recognition of traffic signs among younger drivers.

Despite these insights, several limitations of this study must be acknowledged. First, the experimental trial was conducted within a controlled laboratory environment and did not consider the potential variations caused by vehicle transmission (manual versus automatic), the setup may only partially capture the complexities of real-world driving scenarios. In actual driving conditions, dynamic external factors such as environmental distractions, changing weather, and real-time road complexity could inherently influence blink frequencies and spatial gaze patterns. Lastly, the scope of this investigation was restricted to three functional categories of traffic signs, which may limit the generalizability of the insights regarding other forms of road signage (e.g., electronic variable message signs) that could elicit systematically different visual and cognitive responses.

5. CONCLUSION

Study aims to investigate the visual search patterns and cognitive ergonomic responses of Generation Z drivers across three functional traffic sign designs (Warning, Prohibition, and Instruction signs). Based on the empirical findings, the following conclusions are drawn, the temporal eye-tracking metrics of Blink Duration, Total Fixation Duration, and Dwell Time did not exhibit statistically significant differences, suggesting a baseline uniformity in the microscopic visual processing speeds of Gen Z drivers regardless of sign configurations. Conversely, a highly significant difference was identified in the global distribution of Blink Frequency ($p = 0.001$), driven by a prominent marginal trend exclusively between Prohibition and Warning signs ($p = 0.063$). Warning signs elicited the highest median blink frequency, indicating elevated cognitive workload or transitional visual search demands when processing hazard-based stimuli. Microscopic spatial analysis confirmed a strong directional scanning heuristic, with 91% of initial eye movements directed from the upper-left quadrant to the center of the traffic signs, compared to only 9% from the upper-right. Furthermore, heat map trends indicated a clear preference for glance-based symbolic iconography over alphanumeric characters. Structurally, minimizing the risk of traffic violations for this generation requires shifting driver education toward interactive visual media, such as high-fidelity virtual simulations or short-form video formats. Future research should expand upon these insights by exploring the real-time interaction between blink frequency, gaze patterns, and dynamic traffic sign comprehension under high-stress, real-world driving environments where environmental clutter, distractions, and varied weather conditions can be holistically integrated.

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DECLARATION OF AI-TOOL USAGE

The authors used Gemini (Google) in order to improve language readability, and phrasing. After using this tool, the authors reviewed and edited the contens as needed and takes full responsibility for the content of the publication.