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Cognitive processing of bilingual traffic signs: an eye-tracking study in a driving simulator

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A R T I C L E I N F O

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A B S T R A C T

Multilingual road signage reflects both cultural recognition and the rights of minority language communities. At the same time, it poses challenges for traffic safety, as additional linguistic information may increase visual complexity and cognitive load for drivers. Despite its societal relevance, little empirical evidence exists on how multilingual signage affects driver perception and behaviour in dynamic traffic situations. This study examined the impact of different design variants of multilingual road signs on visual attention and information processing during driving. A mixed-methods approach was used, combining a driving simulator with questionnaire data. Participants ($N = 77$) completed simulated drives on motorway and main road settings while wearing eye-tracking glasses and identified target destinations using a joystick. Experimental scenarios systematically varied in typographic format (italics vs. slash), number of destinations, and road type. Italics consistently supported efficient performance, even when additional destinations were displayed, whereas the slash notation produced faster responses on motorways but slower performance on main roads when destination lists were longer. Fixation durations were less strongly affected but still showed measurable differences, with overall viewing times longer on motorways compared with main roads. Taken together, the results indicate that cognitive processing in bilingual signage is jointly shaped by information density and typographic design. Italics demonstrated robust performance across contexts, facilitating clear visual separation and efficient information uptake, while the slash notation proved advantageous only under specific layout conditions. The findings emphasise that balancing information density with typographic clarity is essential for maintaining legibility and supporting safe driver performance in multilingual road environments.

1. Introduction

Linguistic diversity and its visibility in public spaces are key indicators of democratic participation and cultural recognition. In road traffic, bilingual signage reflects the legal protection of minority languages (Bundesministerium des Innern und für Heimat, 2025a), anchored internationally in the European Charter for Regional or Minority Languages (ECRML, 2024). In Germany, while the Framework Convention for the Protection of National Minorities supports language preservation (Bundesministerium des Innern und

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für Heimat, 2025b; Bundesministerium des Innern und für Heimat, 2025c; Bundesministerium des Innern und für Heimat, 2025d; Bundesministerium des Innern und für Heimat, 2025e) the use of minority languages on traffic signs remains unregulated at the federal level. Neither the German Road Traffic Regulations (StVO) nor technical guidelines (RWBA, RWB) provide binding provisions, leaving implementation to federal states and resulting in significant regional variation (*Gesetz über die Ausgestaltung der Rechte der Sorben/Wenden im Land Brandenburg*, 2024). Standardised rules exist only for foreign-language destinations near national borders (*Richtlinien für die wegweisende Beschilderung auf Autobahnen* 2023, 2024; *Richtlinien für die wegweisende Beschilderung außerhalb von Autobahnen* 2000, 1999). Unlike Spain or the UK, which have established national frameworks (Department for Transport, & Department for Infrastructure (Northern Ireland), Transport Scotland, and Welsh Government, 2018; Ministerio de la Presidencia, 2003; Transport Scotland, 2026), Germany lacks evidence-based guidance. Empirical evidence on the effects of such signage in dynamic traffic remains limited, yet is essential for balancing linguistic inclusion with road safety.

Beyond these legal and regulatory considerations, multilingual signage also presents significant design and cognitive challenges. To reflect the legally recognised role of minority languages, signs should ensure equal visibility and legibility for both languages while remaining clearly structured, easy to understand, and quickly perceptible for drivers (Choe & Mahgoub, 2020; Smahel & Smiley, 2011). However, the integration of additional information increases the risk of visual overload and distraction, often resulting from inconsistent terminology (Jamson, Tate, & Jamson, 2005) or imbalances in typography (Anttila, Luoma, & Rämä, 2000; Hurtado & Chiasson, 2016). Recent research indicates that typographic clarity influences gaze behaviour. Specifically, less legible letterforms and high font complexity lead to longer fixations and slower reading, reflecting increased cognitive processing demands (Lataifeh, Ahmed, Elbardawil, & Gordani, 2024).

The perception of signage occurs within the dynamic context of driving, where visual attention adapts to varying levels of cognitive load (Ma et al., 2020; Witt, Ring, Wang, Kompaß, & Prokop, 2019). Although traffic signs are critical for safety, drivers typically allocate only 200 to 600 milliseconds of visual attention to them (Hudák & Madleňák, 2016; Jiménez, Pérez-Moreno, & Goldaracena, 2025). Multilingual elements compress this critical window by increasing visual complexity, which can prolong reaction times and adversely affecting safety (Wu, Zhao, Lin, & Lee, 2013; Yang et al., 2020). Empirical studies indicate that increasing information density significantly affects fixation behaviour and saccade patterns. While moderate information levels are associated with lower cognitive demand (Han, Du, Wang, & Chen, 2022), excessive volume and high density are linked to elevated driver workload and increased conflict risk, particularly in complex environments (Cai et al., 2024).

Methodologically, the combination of driving simulation and eye-tracking is a widely accepted approach (Babić, Dijanić, Jakob, Babić, & Garcia-Garzon, 2020; Han et al., 2022; Ma et al., 2020; Yang et al., 2020) Some studies report no significant rise in cognitive load caused by bilingual signage, often attributing this to compensatory behaviours, such as reduced speeds, which mitigate the impact of visual complexity (O'Donnell & Trotter, 2025). Nevertheless, consistent evidence shows that both an increased word count and unfamiliar sign formats (Babić et al., 2020; Zhang, Smith, & Witt, 2006) are associated with longer fixation durations. The efficiency of bilingual signage is therefore heavily dependent on layout. Simpler stacked arrangements are associated with shorter reaction times compared with more complex configurations (Cai et al., 2024), while reduced vertical spacing between bilingual text lines can improve both reading speed and accuracy (Zhang, 2021). These findings suggest that compact, well-structured designs support rapid information processing. However, existing studies typically examine isolated design variables or rely on simplified experimental settings. Consequently, there is a lack of evidence regarding how typographic differentiation (e.g., italics) interacts with increasing information density in a dynamic driving context.

To address these gaps, this study systematically varies multilingual layout formats and information load in a high-fidelity driving simulator. By synchronising eye-tracking data with manual reaction times, the study analyses the cognitive trade-offs between linguistic visibility and driver safety.

The primary objective is to evaluate how different multilingual design variants influence gaze behaviour and information acquisition during the driving task. By measuring reaction times via joystick responses alongside eye-tracking data, the study validates gaze-based metrics against the time required for target identification. We hypothesise that italicisation facilitates faster processing through typographic distinction, while information volume exerts an independent effect on fixation durations. These findings aim to provide empirical evidence for signage designs that balance rigorous road safety requirements with the sociolinguistic imperative of linguistic inclusion and cultural recognition.

2. Methodology

To investigate the impact of multilingual signage in road traffic, a mixed-methods approach was adopted, combining a driving simulator study with a questionnaire survey. During the simulated drive, participants' eye movements were recorded using eye-tracking glasses, and joystick inputs indicated when the target destination was identified. Experimental scenarios varied in signage design, road type (motorway vs. main road), and information density. This setup enabled the analysis of different signage configurations in a realistic and controlled environment.

2.1. Participants

Participants were recruited primarily in the area surrounding RWTH Aachen University (Germany) using posters, online announcements, and individual outreach. Additional invitations were distributed via institutional mailing lists. Recruitment took place between 14 May and 5 June 2025. Ethical approval was obtained from the inter-faculty Ethics Committee of RWTH Aachen University (reference number 21/25), and all participants provided written informed consent.

Eligibility criteria included a minimum age of 18 years, German language proficiency, and possession of a valid passenger car driving licence. In total, 79 individuals participated in the driving simulator study.

Some data were excluded due to quality or completeness issues. Two datasets were removed entirely, one due to simulator sickness and one due to major comprehension difficulties. In one additional case, only partial data were used because the participant experienced simulator sickness during the experiment. A small number of individual measurement series were excluded due to technical recording issues.

As a result, the final dataset comprised 77 participants. Not all datasets were equally complete, but all were used in the analyses. The sample was young and mostly male. It consisted of 54 male (70.1%), 22 female (28.6%), and 1 non-binary (1.3%) participant. Driving frequency varied within the group: 22 individuals (28.6%) reported driving (almost) daily, 17 (22.1%) several times per week, 27 (35.1%) several times per month, and 11 (14.3%) only a few times per year. On average, participants had held a valid driving licence for approximately seven years (M = 7.3, SD = 7.0, range = 1–41 years). The reported annual mileage was on average 7700 km (Mean, M), with a standard deviation (SD) of 8304 km/year and a median (Md) of 4800 km/year. In terms of age distribution, 26.0% of participants were aged 18–20 years, 40.3% were 21–25, and 20.8% were 26–30. Smaller proportions were represented in older age groups: 3.9% were 31–35, 5.2% were 35–40, and 3.9% were older than 40. The mean age of the sample was 25.2 years (SD = 7.1, range = 19–59 years). All participants were native speakers of German and unfamiliar with the minority language displayed.

2.2. *Simulator setup and equipment*

The high-fidelity driving simulator at the Institute of Highway Engineering, RWTH Aachen University, enables data collection under standardised and realistic conditions. It provides a continuous 360° traffic environment projected in Full HD at 60 Hz with a viewing distance of 2.5 m. The simulator is based on the chassis of an *E*-Go Life electric vehicle and includes a fully functional car interior to replicate real-world driving conditions (see Fig. 1 (a)). During the experiment, vehicle position, speed, and driver actions such as steering and pedal use were recorded at 50 ms intervals. Engine and ambient sounds were reproduced through an integrated speaker system to enhance realism.

To gather detailed biometric and behavioural data, the study employed Tobii Pro Glasses 3 (see Fig. 1 (b)), a professional-grade eye-tracking system operating at a sampling frequency of 100 Hz. The built-in cameras recorded the driver's field of view, enabling the alignment of gaze behaviour with specific visual elements in the environment. With a mean gaze accuracy of 0.6°, the system allowed for precise mapping of visual attention and fixation. Additionally, a joystick (see Fig. 1 (c)) was installed in the vehicle's centre console, enabling participants to register directional inputs, which were logged during the drive. The joystick was positioned within easy reach and operated without visual attention, allowing participants to keep their focus on the driving task.

This multi-layered setup enabled a comprehensive analysis of visual attention, behavioural responses, and driving performance in a realistic and controlled environment. The combination of eye-tracking, vehicle data, and joystick input provided a robust foundation for examining cognitive processing in response to multilingual road signage.

2.3. *Experimental design and simulation scenarios*

The study combined questionnaire-based data collection with an interactive driving simulation. After completing a demographic questionnaire, participants were fitted with the Tobii Pro Glasses 3 and calibrated using the software's built-in one-point procedure.

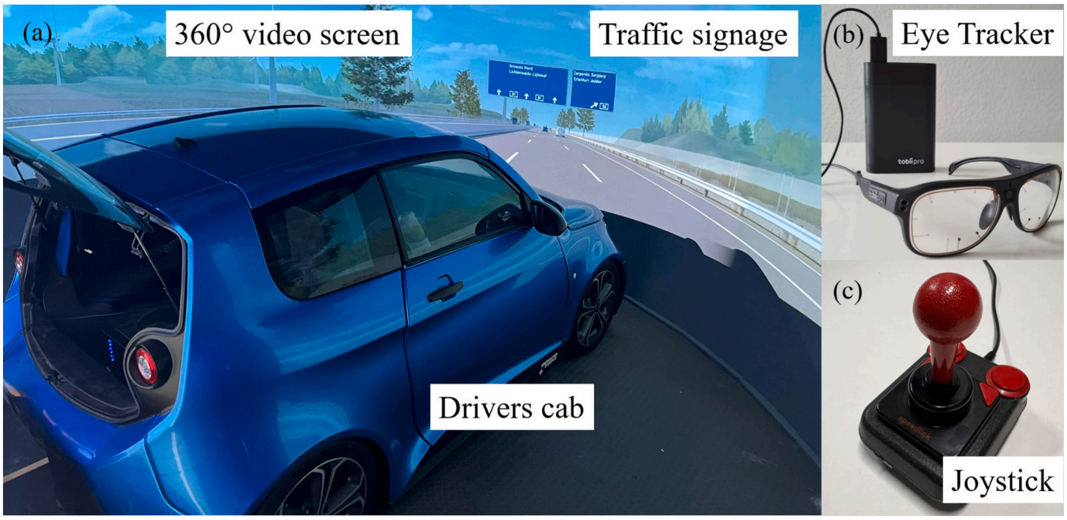


Fig. 1. Driving simulator setup. (a) *E*-Go Life Driver's Cab and partially visible projection screen. (b) Tobii Pro Glasses 3. (c) Joystick for directional input.

Prior to the experiment, participants completed a short familiarisation drive in which joystick operation and the directional selection task were explained. The specific aim of the study was not disclosed to avoid potential bias.

A repeated-measures design was used, with each participant encountering several traffic signs in fully randomised order. The simulated environment included motorway and main road settings with systematic variation in signage design. Manipulated variables comprised typographic format (italics vs. slash), number of destinations, and their ordering.

A total of 16 different signs were used in the full study. Due to time constraints, each participant was exposed to a maximum of 15 randomly assigned signs, ensuring sufficient variation while maintaining a manageable session length. The present paper focuses on a subset of seven signs (see Fig. 2 and Fig. 3), representing key design conditions. Signs 13 and 2 represent status quo layouts for main roads and motorways, respectively, and include the maximum number of destinations permitted for each road type. The alternative designs vary in the number of destinations and the presentation format of the minority language (italics vs. slash).

Participants were instructed to locate the destination on the upcoming road sign and indicate the correct direction using a joystick (left, right, or forward). Only the first joystick input was recorded for analysis, and no correction was permitted. Incorrect responses were rare (1.2% of trials) and therefore retained but not analysed separately. Each scenario featured one traffic sign and lasted 15–20 s. To standardise presentation conditions, the traffic signs were displayed as fixed pop-up overlays that moved synchronously with the vehicle, ensuring consistent visibility, legibility, and exposure time across all participants regardless of driving speed or lane position.

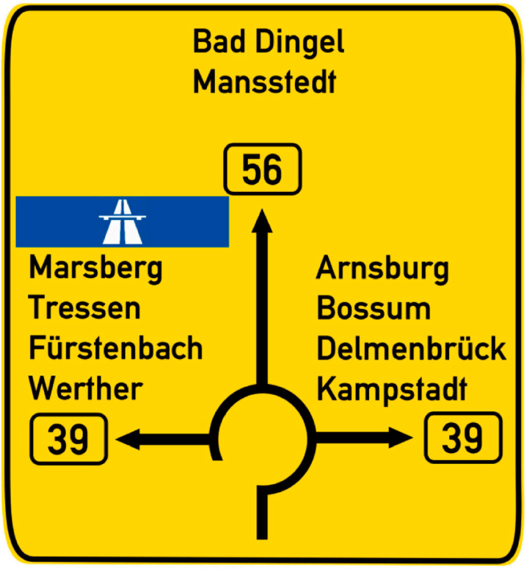
Participants were free to choose their driving speed and direction within the typical speed range of the respective road class. The display duration of the signs was predefined and independent of driving speed, ensuring equal reading time across participants. This controlled presentation differs from a natural roadside setup but was implemented to maintain uniform viewing conditions for experimental comparison. The sign presentation and joystick input occurred several seconds before the end of each scenario, leaving

(a) Sign 13

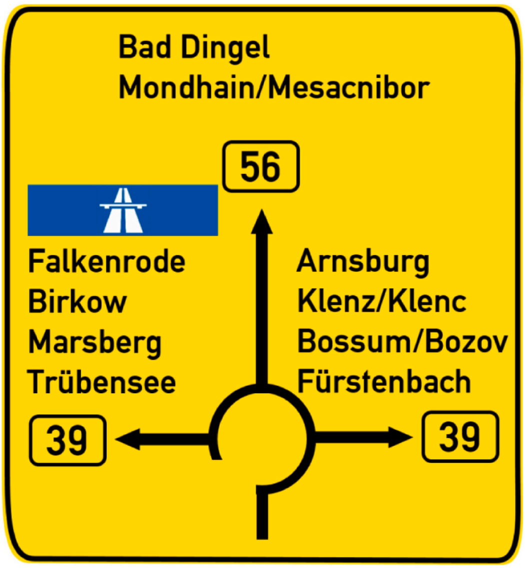
(b) Sign 16

(c) Sign 17

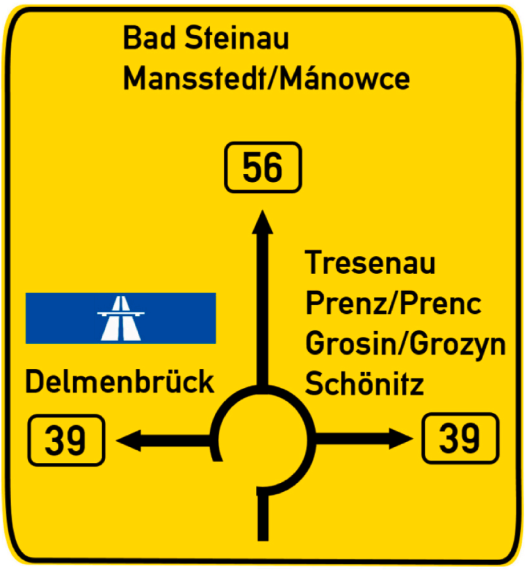
Fig. 2. Visual stimuli used in the eye-tracking study for motorway signage. (a) Baseline condition on highway with 7 destinations. (b) Bilingual sign with minority language replacing some German destinations, presented in *italics*. (c) Bilingual sign with minority language replacing some German destinations, separated by a slash.



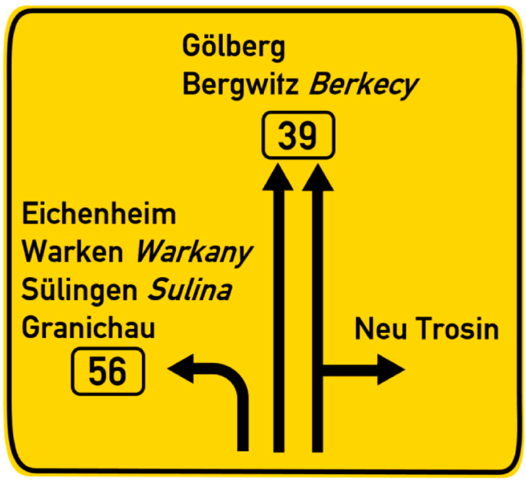
(a) Sign 2



(b) Sign 4



(c) Sign 6



(d) Sign 5

Fig. 3. Visual Stimuli Used in the Eye-Tracking Study for Main Road condition. (a) Monolingual baseline condition on main road with 10 destinations. (b) Bilingual sign with minority language added to existing German destinations separated by a slash. (c) Bilingual sign with minority language replacing some German destinations separated by a slash. (d) Bilingual sign with minority language presented in *italics as counterpart to (c)*.

Table 1
Number of valid samples, incorrect responses (included in valid samples), and no-input cases (excluded from analysis) for reaction times and valid fixation time samples, separated by road category and sign variant.

Road category		Motorway			Main road			
Sign number		Sign 13	Sign 16	Sign 17	Sign 2	Sign 4	Sign 6	Sign 5
Target destination		Tann-weiler	Erlenfurt	Neubrück	Delmenbrück	Bossum	Grosin	Sülingen
	Valid samples	45	41	75	75	44	42	43
Reaction time	Incorrect responses	1	0	3	1	1	0	0
	No input	2	3	1	2	0	0	1
Fixation Time	Valid samples	44	39	63	65	37	34	34

sufficient time to complete the task. A visual transition cue indicated the start of the next scenario, allowing participants to prepare for the upcoming situation.

Motorway signs were displayed for 6.4 s and main road signs for 4.0 s, based on empirically derived reading times (Färber & Färber, 2009) plus a one-second buffer to account for reaction time. This buffer also corresponds to reaction times commonly assumed in traffic safety contexts, for example in the calculation of stopping distances (Dettinger, 2008). Because signs appeared abruptly rather than being gradually approached, a fixed presentation duration was necessary to ensure sufficient legibility under simulator conditions. This represents a methodological limitation.

Table 1 summarises the number of valid measurements obtained for each sign, including valid samples with responses and trials without input. The number of usable measurements varied slightly across signs. Trials without input occurred only rarely (0–3 per sign) and were excluded from further analysis. Most of these cases resulted from participants briefly losing track of the target destination while approaching the sign.

Incorrect responses were retained in the valid sample but not analysed separately, as they accounted for only 1.2% ($N = 11$) of all trials. Reaction times shorter than 0 s or exceeding the sign presentation duration by more than two seconds were excluded as implausible ($N_{Motorway} = 1$; $N_{Mainroad} = 1$). The additional two-second margin accounted for delayed responses while maintaining realistic task constraints. Fixation times exceeding the respective presentation duration were removed due to technical recording errors ($N_{Mainroad} = 2$).

Following the simulation, participants completed a post-drive questionnaire addressing the signage they had encountered, allowing for triangulated analysis of gaze data, behavioural responses, and subjective impressions.

2.4. Measurements

To investigate the effectiveness of navigation aids and overall driving efficiency, the driving simulator study primarily utilised the following data sources: a questionnaire, simulator data and eye movement data.

2.4.1. Questionnaire

To assess participants' subjective evaluations of multilingual road signage, a questionnaire was employed. In addition to collecting demographic information, the questionnaire included a post-simulation section focusing on the visual implementation of minority languages. Participants evaluated four signage variants: two from the motorway condition (see Fig. 2 (a-b)) and two from the main road condition (see also Fig. 3 (c-d)), including one using italics and one using a slash to implement the minority language. These four variants were selected as exemplary cases from the broader set of signs presented. Each block consisted of one signage variant followed by six Likert items, presented sequentially. For each sign, participants rated six predefined usability criteria (comprehensibility, intuitiveness, legibility, visual structure, processing time and language differentiation) based on the statements listed in Table 2.

The evaluation was carried out using a five-point Likert scale (1 = strongly disagree to 5 = strongly agree). Each participant assessed all four signage variants in full. To minimise order effects, both the presentation order of the signs and the sequence of the usability criteria were randomised for each participant.

After completing these evaluations, participants answered a forced-choice item indicating their general preference between the two formatting styles (italics or slash) for implementing minority languages in directional road signage.

The questionnaire aimed to capture participants' subjective perceptions of clarity, readability and usability in order to identify potential advantages or drawbacks of different design implementations for minority language integration in traffic signage.

2.4.2. Driving simulator measures

2.4.2.1. Reaction time.

In addition to the subjective assessments, objective reaction times (RT) were recorded in the driving simulator. Reaction time was defined as the time in milliseconds between the appearance of the sign and the first joystick response. Prior to the start of each scenario, the target destination was communicated to participants via a brief on-screen text in order to ensure that the subsequent reaction specifically referred to the relevant destination. During the simulated drive, participants were instructed to identify the direction of the indicated destination based on the signage and to respond accordingly. Reaction time was recorded as an objective indicator of the efficiency of visual information intake and processing under realistic conditions.

This measurement allows for the detection of possible delays in cognitive processing that may arise due to differences in sign design or complexity. To explore such effects, reaction times were analysed by comparing median and mean values across conditions,

Table 2
Usability Criteria for Evaluating Multilingual Road Signs based on questionnaire.

Usability Criteria	Statement
Comprehensibility	I can easily understand the objectives on the sign despite the additional minority language.
Intuitiveness	The addition of minority languages seems intuitive to me and does not interfere with understanding.
Legibility	All destination names, including those in minority languages, are easy to read.
Visual structure	Despite the multilingualism, the sign is clearly laid out.
Processing time	I can grasp the multilingual target designations without losing time.
Language distinction	The distinction between the different languages on the sign is clearly recognisable to me.

enabling a robust representation of central tendencies. Boxplots were used to visualise distributional differences between signage variants and road categories.

2.4.2.2. Gaze behaviour. In addition to reaction times, participants' gaze behaviour was recorded using eye-tracking technology. The aim of the eye-tracking analysis was to examine visual attention and information processing when interacting with multilingual road signs. Key metrics included fixation time (FT) and total gaze duration within predefined Areas of Interest (AOIs). These measures allowed the analysis of visual attention allocation to different elements of the signage.

Eye-tracking data were processed using Tobii Pro Lab Analyzer Edition. The software enabled fixation-based metric extraction and the visualisation of gaze behaviour. Data quality was high, with a median proportion of valid gaze samples of 98% (range: 88–100%). For AOI analysis, a static approach was applied. A screenshot was captured at a predefined position during the presentation of the traffic sign. AOIs were defined on this reference image. Gaze samples recorded while the sign was visible were mapped to these predefined AOIs. This ensured consistent AOI boundaries across participants. Given the viewing distance and the close spatial proximity of the bilingual text elements, AOIs were defined at sign level rather than at the level of individual language fields. This approach ensured robust fixation assignment and enabled reliable comparisons of overall gaze allocation patterns across signage variants.

Fig. 4 illustrates the spatial layout of the predefined AOIs for the motorway scenario. The AOIs covered key elements of the visual scene, including traffic signs, the roadway, vehicle display, and mirrors. For the main road scenario, AOIs were adjusted to reflect the different environmental layout. These areas formed the basis for quantifying and comparing gaze behaviour across signage variants and road classes.

As a complement to the reaction time measurements, the eye movement metrics provide a robust methodological approach for evaluating the usability and cognitive demands of multilingual signage. Patterns such as a higher number of fixations or longer dwell times were interpreted as potential indicators of increased cognitive load or reduced intuitiveness of the design. The reconstruction of gaze paths also enabled the identification of differences in visual processing that can be attributed to the design features of the signage, including the presence and format of minority languages.

2.5. Statistics

The statistical analysis of the collected data was carried out using IBM SPSS Statistics (version 29.0.2.0) and Python (version 3.11). Eye-tracking data were analysed using Tobii Pro Lab Analyzer Edition, a software tool specifically designed for evaluating data captured with the Tobii Pro Glasses 3. The software enabled precise identification of fixation points, fixation durations, and saccade paths for each road sign, which were analysed in relation to predefined Areas of Interest. This allowed for a detailed assessment of overall visual attention patterns in relation to predefined sign regions and layout characteristics.

Descriptive statistics were calculated to summarise demographic characteristics as well as reaction and fixation times, which are reported as medians with interquartile ranges (IQR), and questionnaire ratings, which are reported as means with 95% confidence intervals. To examine differences in Likert-scale responses across signage designs (e.g., legibility, comprehensibility, processing time),

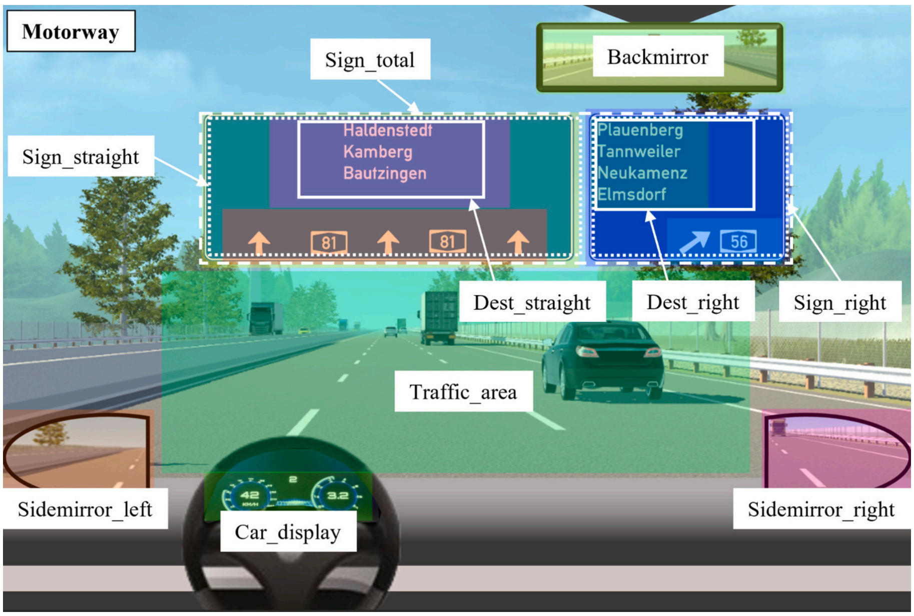


Fig. 4. Definition of Areas of Interest (AOIs) for Eye-Tracking Analysis in the Motorway Simulation Scenario. The labelled AOIs (for example signs, destinations, mirrors, car display or traffic area) indicate the specific regions in the driver's field of view that served as the basis for the analysis of fixations and gaze durations.

paired-samples *t*-tests were applied. To control for the increased risk of Type I errors across the six correlated usability criteria, *p*-values were adjusted using the false discovery rate (FDR) procedure according to Benjamini–Hochberg (Roberson, Shema, Mundfrom, & Holmes, 1995). This approach provides balanced control of false positives without unduly reducing statistical power and is particularly suitable for exploratory designs with multiple dependent comparisons (Benjamini & Hochberg, 1995; Benjamini & Yekutieli, 2001). Results are reported as mean differences (ΔM) with corresponding 95% confidence intervals and FDR-adjusted p-values (p_{FDR}).

To compare signage variants, separate linear mixed-effects models were fitted for each road type (motorway and main road) and for each dependent variable (reaction time and fixation time) on the log scale: $\log(Y) \sim C(\text{sign}) + (1|\text{participant})$. Separate models were used because signage sets differed between road types and were not directly comparable. Sensitivity analyses including crossed random intercepts for participants and signs, and participant-specific random slopes for format (italic vs. slash), yielded comparable results. Model assumptions were assessed using residual and Q–Q plots (Fig. 5), indicating approximate normality and homoscedasticity. Pre-specified contrasts were tested using two-sided Dunnett comparisons with Holm-adjusted *p*-values; additional pairwise comparisons were derived from fixed-effect estimates and likewise Holm-adjusted. Effects are reported as log-differences and back-transformed geometric mean ratios ($GMR = \exp.(\Delta)$) with 95% confidence intervals.

As an exploratory complement to the mixed-effects models, Pearson correlations between log-transformed fixation and reaction times were computed to assess the association between visual attention and behavioural responses across road types and sign formats. All tests were two-tailed ($\alpha = 0.05$). Because participants evaluated multiple stimuli, results were interpreted with caution regarding the lack of full independence.

3. Results and discussion

The following sections present the results concerning the subjective and objective evaluation of bilingual road signs. The analysis is structured according to data source and distinguishes between motorway and main road contexts. Because signage layouts differed between road types, results are reported separately for motorway and main road conditions.

3.1. *Perceived usability of typographic styles*

Across both road types, the comparison between italic and slash formatting of bilingual signs revealed that italics were consistently rated more favourably, although the strength and significance of the effects varied with driving context (see Fig. 6 and Fig. 7). On

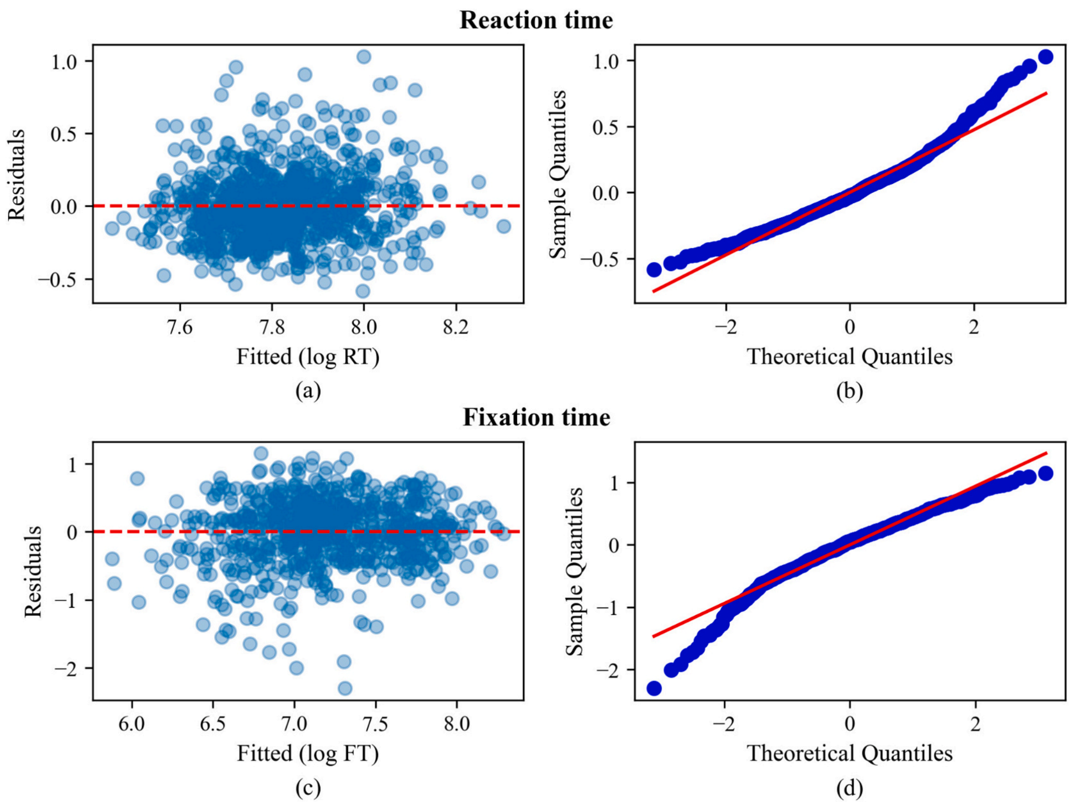


Fig. 5. Residual diagnostics for the mixed-effects models of reaction time and fixation time. (a) Residuals vs. fitted values for RT, (b) Q–Q plot of residuals for RT, (c) Residuals vs. fitted values for FT, (d) Q–Q plot of residuals for FT.

motorways, participants' ratings on the five-point Likert scale (1 = strongly disagree, 5 = strongly agree) indicated significant advantages of italics in five out of six usability criteria. Comprehensibility was rated higher for italics (M = 4.42) than for slash (M = 4.17), with a mean difference of ΔM = 0.25 (95% CI [0.05, 0.44], $p_{FDR} = 0.028$). Intuitiveness followed the same pattern (M = 3.95 vs. 3.60, ΔM = 0.35, 95% CI [0.03, 0.67], $p_{FDR} = 0.049$). Processing time also showed a clear significant advantage for italics (M = 3.68 vs. 3.26, ΔM = 0.42, 95% CI [0.10, 0.74], $p_{FDR} = 0.028$). The strongest effect emerged for language distinction, where italics received a mean score of 4.26 compared to 3.55 for slash (ΔM = 0.71, 95% CI [0.37, 1.06], $p_{FDR} = 0.001$). By contrast, visual structure did not reach significance (M = 4.36 vs. 4.13, ΔM = 0.23, 95% CI [−0.02, 0.49], $p_{FDR} = 0.086$), and legibility showed no difference at all between formats (M = 4.57 vs. 4.57, ΔM = 0.00, 95% CI [−0.17, 0.17], $p_{FDR} = 1.000$).That legibility did not differ suggests that italics do not change basic perceptual clarity, but rather that alternative typography influences how information is cognitively organised and processed (Lewis & Walker, 1989).

On main roads, the observed differences were less pronounced, but followed the same overall pattern. A significant effect was found only for language distinction (M = 3.69 vs. 3.10, ΔM = 0.58, 95% CI [0.20, 0.97], $p_{FDR} = 0.020$). For the remaining five criteria, no statistically reliable differences were observed. Comprehensibility showed a mean difference of ΔM = 0.31 (95% CI [0.04, 0.58], $p_{FDR} = 0.075$), intuitiveness ΔM = 0.26 (95% CI [−0.05, 0.57], $p_{FDR} = 0.147$), legibility ΔM = 0.17 (95% CI [−0.03, 0.37], $p_{FDR} = 0.147$), visual structure ΔM = 0.25 (95% CI [−0.10, 0.59], $p_{FDR} = 0.185$), and processing efficiency ΔM = 0.21 (95% CI [−0.10, 0.52], $p_{FDR} = 0.187$). Although all mean values were numerically higher for italics, the confidence intervals for these differences included zero, indicating that these trends were not statistically reliable and should be interpreted with caution.

From a traffic psychology perspective, these results suggest that italics support a clearer separation between languages in subjective perception. In the preference task, 64.9% of participants selected the italic variant ($N = 50$; 95% CI [0.532–0.755]), whereas 35.1% chose the slash notation ($N = 27$; 95% CI [0.245–0.468]). A binomial test against equal choice probability confirmed that this difference was statistically significant ($p = 0.012$). In contrast, the slash notation separates words only through punctuation, while the overall font remains the same. This may be perceived as less effective for distinguishing the two languages. A likely explanation is that the use of a different font style inherently signals a boundary between language versions, making the italic presentation easier to distinguish at a glance. This corresponds with the assumption that a change of typeface represents an efficient strategy for conveying the author's intended meaning. (McAteer, 1989) In addition, previous evidence indicates that italics do not impair reading performance when combined with neutral fonts, which may hinder letter recognition (Dyson & Beier, 2016). In combination with the perceived visual separation, this makes italics particularly well suited for emphasising content without reducing legibility. This interpretation is consistent with research showing that typographic differentiation supports visual grouping and reduces cognitive load during information processing (Lataifeh et al., 2024). Similar effects have also been reported for multilingual signage, where clearer separation between language elements facilitates faster visual parsing and improves comprehension, particularly under limited viewing time (Cai et al., 2024; Zhang, 2021).

Taken together, the pattern of results was consistent across both road types, with italics generally receiving higher ratings. This suggests that subjective perception of bilingual signs is largely independent of traffic context (Jamson et al., 2005). For practical implementation, however, it is important that information can also be processed efficiently under higher cognitive load, as on motorways (Lyu, Xie, Wu, Fu, & Deng, 2017). Because these judgments were based on static presentations, the following section tests whether typographic separation also affects behavioural performance.

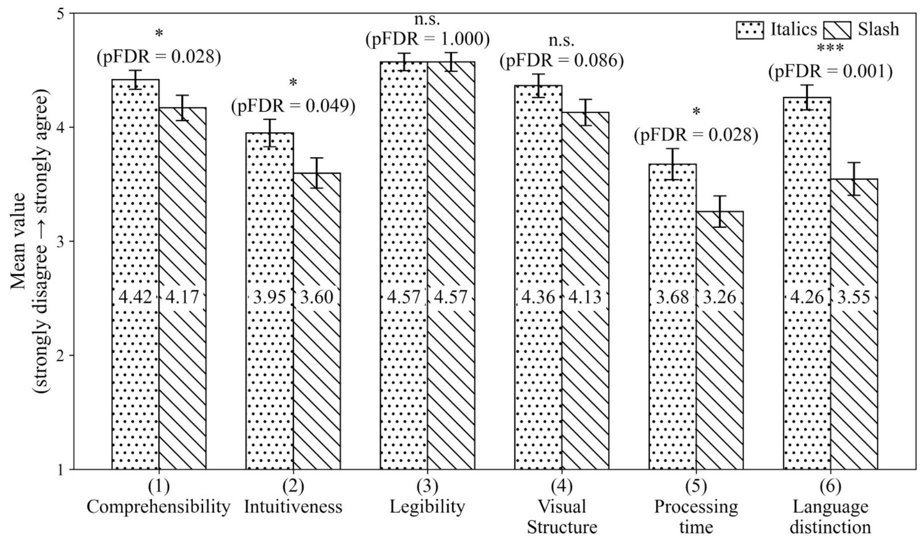


Fig. 6. Mean ratings (± SE) for six usability criteria of bilingual road signs (motorway condition: italics vs. slash).

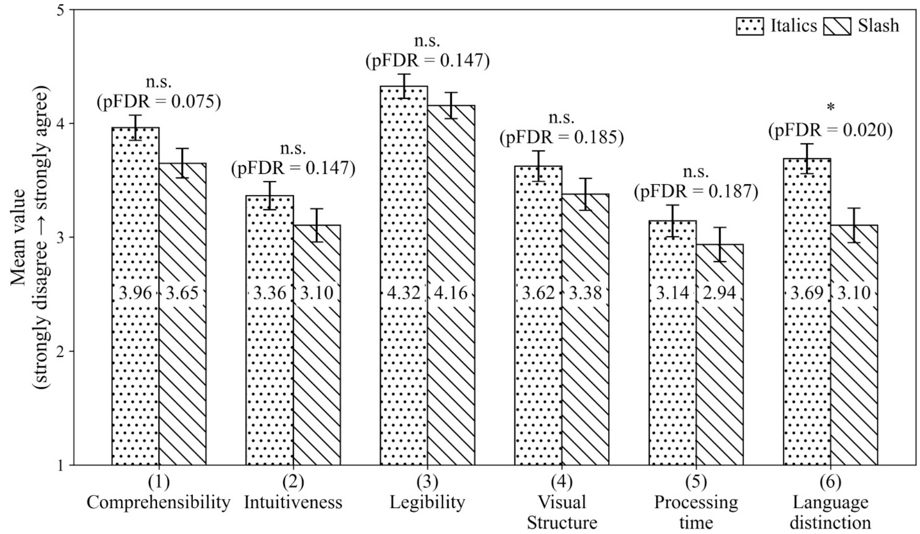


Fig. 7. Mean ratings (± SE) for six usability criteria of bilingual road signs (main road condition: italics vs. slash).

3.2. Reaction times in driving simulation

The analysis of reaction times on main roads revealed clear differences between sign variants (see Fig. 8). In the boxplots, the bold horizontal line represents the median, the boxes indicate the interquartile range (IQR), the whiskers extend to the most extreme values within 1.5 × IQR from the quartiles, and dots beyond the whiskers denote outliers. Descriptively, the median for the baseline condition (Sign 2; Md = 2608 ms, IQR = 2162–3082) was comparable to Sign 6 (Md = 2516 ms, IQR = 2171–3062). The spread of the distributions also differed between conditions. Sign 4 showed a wider interquartile range and several high-value outliers, indicating increased variability in processing times when additional destinations were presented. In contrast, the italic condition (Sign 5) displayed a more compact distribution, indicating less variability across participants. The presence of outliers across conditions indicates occasional prolonged inspection periods, which are typical for visual search tasks under varying levels of information density.

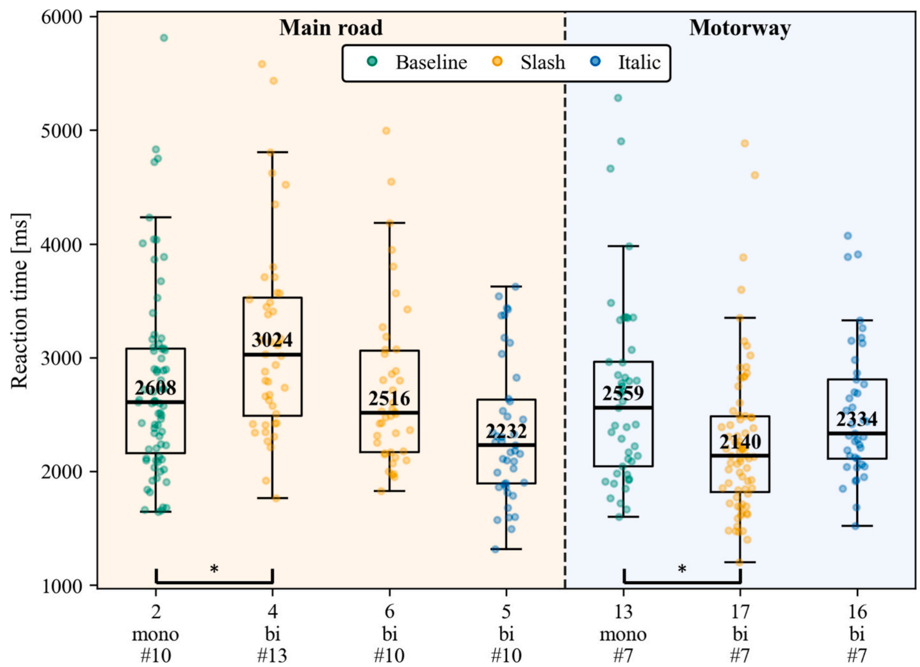


Fig. 8. Reaction times [ms] until the target destination was identified, displayed separately by sign (number, mono- or bilingual, number of destinations), typographic style (baseline, italic or slash) and road type (main road vs. motorway). Asterisks (*) indicate statistically significant differences between conditions ($p < 0.05$).

Consistently, the mixed-effects model (see Table 3) indicated no significant difference between Sign 6 and the baseline (Δlog = 0.001, GMR = 1.001, 95% CI [0.920–1.088]; p_{Holm} = 1.00), reflecting a negligible effect. By contrast, Sign 4 yielded significantly longer reaction times relative to the baseline (Md = 3024 ms, IQR = 2488–3529; Δlog = +0.148, GMR = 1.159, 95% CI [1.067–1.258]; p_{Holm} = 0.0018), suggesting that the additional number of destinations increased cognitive load and slowed target identification (Lyu et al., 2017; Xie, Li, Wu, & Lyu, 2025). This represents a clear medium-sized effect of approximately 16%. Sign 4 also exhibited greater dispersion towards longer reaction times, suggesting increased inter-individual variability in processing behaviour when additional destinations increased information density. This variability suggests that increased information density did not affect all drivers equally, but may have amplified differences in individual search and processing strategies. The direct comparison between Sign 5 (italics; Md = 2232 ms, IQR = 1894–2630) and Sign 6 (slash) indicated 13.7% shorter reaction times for the italics variant (Δlog = −0.147, GMR = 0.864, 95% CI [0.778–0.959]). This corresponds to an average time advantage of about 0.28 s, or roughly 5.5 m at a typical main road speed of 70 km/h. Although the geometric mean ratio suggests a potential effect, the difference did not reach statistical significance after Holm adjustment (p_{Holm} = 0.110) and should therefore be interpreted cautiously within the context of this dataset. Nevertheless, the observed effect size may still be considered practically meaningful. Even though such differences may appear small in absolute terms, they can be critical in real traffic situations, as a few meters may determine whether drivers have sufficient time to detect, interpret, and respond to road signs safely. This finding suggests that italics may provide a clearer visual boundary between the two languages, making it easier for drivers to disregard the non-relevant language and focus on the target destination (Jamson, 2004; Jamson et al., 2005). By contrast, the italic condition showed a comparatively more compact distribution, suggesting more consistent processing behaviour across participants. Overall, the results for main roads demonstrate that both the amount of information and the mode of typographic separation influence reaction times. The strongest effects were associated with increased information density. This finding aligns with previous studies demonstrating that increasing information density leads to longer fixation durations and higher cognitive workload in traffic sign perception (Cai et al., 2024; Han et al., 2022). The present results extend these findings by showing that typographic differentiation between languages, particularly through italics, can partially compensate for increased information load by facilitating faster target identification. (See Table 4.)

On the motorway, where all signs contained the same number of destinations, a different pattern emerged. Descriptively, the median reaction time for the baseline (Sign 13; Md = 2559 ms, IQR = 2043–2966) was higher than for both the italics variant (Sign 16; Md = 2334 ms, IQR = 2110–2809) and the slash variant (Sign 17; Md = 2140 ms, IQR = 1819–2483). The mixed-effects model revealed no significant difference between the italics condition and the baseline (Δlog = −0.042, GMR = 0.959, 95% CI [0.863–1.065]; p_{Holm} = 0.863), reflecting a very small effect. By contrast, Sign 17 (slash) produced significantly shorter reaction times than the baseline (Δlog = −0.165, GMR = 0.848, 95% CI [0.776–0.927]; p_{Holm} = 0.0011), corresponding to a robust effect of approximately 15% faster responses. The direct comparison between Signs 16 and 17 further suggested 12.5% faster responses for the slash condition (Δlog = +0.123, GMR = 1.131, 95% CI [1.031–1.210]; p_{Holm} = 0.072), although this result did not reach statistical significance. The numerical magnitude nonetheless reflects a moderate effect. Compared with the main-road conditions, the motorway variants showed more strongly overlapping distributions and narrower interquartile ranges, reflecting more homogeneous response patterns across participants under lower information density.

These findings point to slash notation as the more efficient format for processing bilingual information on motorways, as reflected in faster reaction times. In contrast, italics did not yield a measurable speed advantage relative to the baseline but were consistently rated more favourably in subjective evaluations. Taken together, this pattern suggests a trade-off between processing speed and cognitive organisation: slash notation may facilitate rapid visual parsing, whereas italics appear to support clearer structuring of information and easier integration into drivers' mental representations. A possible explanation is the compact horizontal structure of the slash notation, which reduces vertical scanning and allows both language versions to be processed within a single fixation. This may be particularly advantageous on motorways, where higher speeds increase time pressure and favour rapid, glance-based information acquisition (Lyu et al., 2017). In contrast, vertically separated layouts may require additional gaze shifts, which become more critical under high-speed driving conditions.

Taken together, the results indicate that reaction times are shaped by both the amount of information and the way in which two languages are visually separated. When the number of destinations increases, reaction times lengthen, as seen for Sign 4 on main roads. By contrast, when the number of destinations remains constant because some German destinations were omitted and others presented in bilingual form, the overall information load does not increase. Under these conditions, drivers seem able to ignore the non-relevant

Table 3
Results of the linear mixed-effects models for reaction times across main road (baseline = Sign 2) and motorway (baseline = Sign 13) conditions, including pairwise comparisons between Signs 5 vs. 6 and 16 vs. 17. Asterisks (*) indicate statistically significant differences between conditions ($p < 0.05$).

Road type	Comparison (Sign number)	Δlog (Standard error)	GMR	95%-CI (GMR)	p_{Holm}
Main road	4 vs 2	+0.148 (0.042)	1.159	1.067–1.258	0.0018*
	6 vs 2	0.001 (0.043)	1.001	0.920–1.088	1.000
	5 vs 6	−0.147 (0.053)	0.864	0.778–0.959	0.110
Motorway	16 vs 13	−0.042 (0.054)	0.959	0.863–1.065	0.863
	17 vs 13	−0.165 (0.045)	0.848	0.776–0.927	0.0011*
	16 vs 17	+0.123 (0.047)	1.131	1.031–1.210	0.072

Table 4
Results of the linear mixed-effects models for fixation times across main road (baseline = Sign 2) and motorway (baseline = Sign 13) conditions, including pairwise comparisons between Signs 5 vs. 6 and 16 vs. 17.

Road type	Comparison (Sign number)	Δlog (Standard error)	GMR	95%-CI (GMR)	p_{Holm}
	4 vs 2	+0.268 (0.109)	1.307	1.055–1.620	0.056
Main road	6 vs 2	+0.040 (0.113)	1.041	0.834–1.298	0.723
	5 vs 6	−0.147 (0.053)	0.864	0.778–0.959	0.110
	16 vs 13	−0.062 (0.089)	0.940	0.789–1.119	0.975
Motorway	17 vs 13	−0.044 (0.076)	0.957	0.825–1.110	0.975
	16 vs 17	−0.018 (0.079)	0.982	0.841–1.148	1.000

language. Variations in script form help establish clear reading units and separate words from each other (Catach, 1998), thereby facilitating processing and leading to shorter reaction times. This mechanism likely explains the reduced latencies observed for both italics and slash variants compared with the baseline. Among these, italics offered advantages on main roads, whereas slash separation performed best on motorways. Sensitivity analyses confirmed the robustness of these findings, with no evidence of violations of model assumptions.

Comparing subjective ratings with behavioural performance revealed only a partial correspondence between perceived usability and objective processing efficiency. Italics were consistently rated more favourably in terms of language distinction, intuitiveness, and processing clarity, yet did not always yield the fastest reaction times. In contrast, the slash format produced faster responses under motorway conditions despite receiving lower subjective evaluations. This divergence suggests that subjective impressions of readability and objective processing efficiency capture partly different aspects of sign perception and cognitive demands during driving. Similar dissociations between subjective readability judgments and objective visual performance have also been reported in typography research, where perceived readability did not necessarily correspond to measurable differences in reading efficiency (Baraggioli & Brasel, 2008).

One possible explanation is that italics support clearer cognitive structuring of bilingual information and facilitate conscious language distinction, which is reflected in subjective evaluations. Slash notation, by contrast, may promote more compact visual parsing and shorter scanning paths under low-information conditions, thereby supporting rapid target detection despite lower perceived clarity. These findings underline the importance of combining subjective and objective measures when evaluating multilingual signage design.

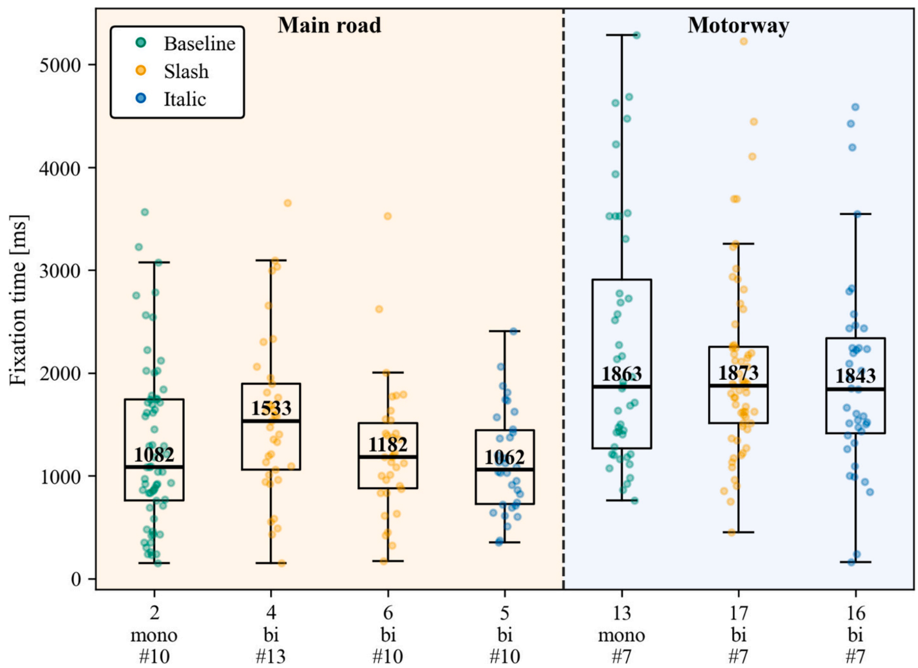


Fig. 9. Duration of fixation [ms] on the full sign (AOI 'Sign_total'), displayed separately by sign (number, mono- or bilingual, number of destinations), typographic style (baseline, italic or slash) and road type (main road vs. motorway).

3.3. Eye-tracking results on gaze behaviour

In contrast to the reaction time analysis, the linear mixed-effects model did not reveal significant differences in fixation durations across the sign conditions (see Fig. 9). Here, fixation duration refers to the total viewing time of the entire sign area (see Fig. 4, AOI 'Sign_total').

On main roads, the baseline (Sign 2) showed a median fixation time of 1082 ms (IQR = 761–1743). Relative to this baseline, fixation times increased for Sign 4, which included additional destinations (Md = 1533 ms, IQR = 1062–1893), corresponding to a substantial but non-significant 30.7% increase in the mixed model (Δlog = +0.268, GMR = 1.307, 95% CI [1.055–1.620]; p_{Holm} = 0.056). Compared with the baseline, fixation durations for Sign 4 were generally shifted towards higher values, suggesting increased visual processing demands when additional destinations were presented. For Sign 6, which contained the same number of destinations as the baseline but separated by slashes, fixation times were also slightly longer (Md = 1182 ms, IQR = 879–1510; Δlog = +0.040, GMR = 1.041, 95% CI [0.834–1.298]; p_{Holm} = 0.723). This suggests that slash separation may demand additional processing time, consistent with subjective reports from the questionnaire indicating longer perceived processing for the slash variant. By contrast, Sign 5 (italics; Md = 1062 ms, IQR = 726–1445) was slightly faster than the baseline, and displayed a comparatively more compact distribution, suggesting more consistent fixation behaviour across participants. The direct comparison between Sign 5 and Sign 6 confirmed only a small numerical difference in fixation durations (Δlog = −0.174, GMR = 0.864, 95% CI [0.778–0.959]; p_{Holm} = 0.110), reflecting a modest but not statistically reliable effect. Outliers were observed across all conditions and likely reflect occasional prolonged inspection periods during visual search.

Taken together, these findings indicate that the inclusion of additional minority language destinations tends to increase visual processing demands on main roads. This pattern is consistent with previous eye-tracking studies showing that additional destinations and higher information density increase visual search time, fixation duration, and cognitive workload during sign reading (Cai et al., 2024; Han et al., 2022). Similarly, earlier work has reported that unfamiliar or additional languages on road signs can increase cognitive load and impair driving performance (Liu, Zhao, Li, & Li, 2022). By contrast, italics appear to provide a more efficient means of separating language versions, showing the numerically largest reduction in fixation time among the variants, even though the effects did not reach statistical significance.

For the motorway condition, fixation times were overall longer than on main roads. At the same time, slash formatting yielded faster reaction times despite this increase, suggesting that the notation may have facilitated a more efficient search strategy. One interpretation is that drivers invested slightly more time in fixations, but with fewer or more targeted gaze transitions, allowing them to locate the relevant information more quickly overall. Analyses of gaze-transition matrices could help to clarify this mechanism, for example by testing whether slash reduces the number of shifts between language fields compared to italics. Within the motorway condition, however, fixation durations were highly comparable across variants. The baseline (Sign 13) showed a median of 1863 ms (IQR = 1265–2908), while the italics variant (Sign 16; Md = 1843 ms, IQR = 1413–2339) was slightly lower and the slash variant (Sign 17; Md = 1873 ms, IQR = 1513–2254) slightly higher, but both yielded nearly identical values. Although several conditions exhibited relatively long upper whiskers, the interquartile ranges overlapped substantially, indicating comparable central response patterns across typographic formats. In the mixed model, neither Sign 16 (Δlog = −0.062, GMR = 0.940, 95% CI [0.789–1.119]; pHolm = 0.975) nor Sign 17 (Δlog = −0.044, GMR = 0.957, 95% CI [0.825–1.110]; pHolm = 0.975) differed significantly from the baseline. Likewise, the direct comparison between Signs 16 and 17 revealed no reliable difference (Δlog = −0.018, GMR = 0.982, 95% CI [0.841–1.148]; pHolm = 1.00). These results indicate that, on motorways where the number of destinations was constant, the mode of typographic separation (italics vs. slash) did not substantially affect fixation durations, with both variants performing comparably to the baseline.

In summary, fixation times were generally shorter than reaction times, reflecting the distinct cognitive processes underlying eye movements compared with manual responses. As Sereno and Rayner (Sereno & Rayner, 2000) note, fixation times during reading are typically shorter than reaction times because additional time is required for lexical processing. This also aligns with previous findings showing that fixation times can be shorter than reaction times under time pressure, as a preliminary code of the stimulus is obtained

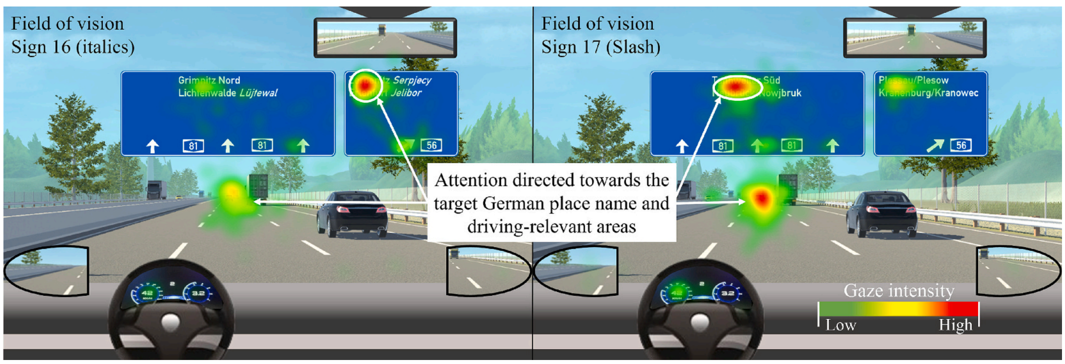


Fig. 10. Heatmaps of gaze fixation distributions during sign presentation for motorway signs with italics (Sign 16, left) and slash separation (Sign 17, right), aggregated across all participants. Both signs are also shown in Fig. 2.

and used as a starting point for further analysis (Sanders & Rath, 1991). On main roads, fixation times broadly mirrored the reaction time pattern, with the addition of minority language destinations leading to longer processing demands and italics emerging as the relatively more efficient separation method. On motorways, by contrast, fixation durations were overall longer but stable across conditions, suggesting that in this context neither italics nor slash separation confers a measurable advantage.

While fixation times indicate only the overall duration of viewing a sign, the heatmaps provide additional information on where these fixations occurred within the visual scene during the 6.4 s presentation window of the sign. Fig. 10 illustrates this for two motorway sign variants, with italics on the left and slash separation on the right. Areas shown in red correspond to high fixation density, whereas green indicates lower fixation intensity. In both variants, the most intense clusters of gaze are directed towards the target destinations (Erlenfurt and Neubrück). By contrast, only sparse and scattered fixations appear in the regions displaying the additional minority-language names. Further clusters are visible on the directional arrows, which served route guidance, as well as on the roadway and the preceding vehicle, reflecting monitoring of driving-relevant areas.

To complement the qualitative heatmap visualisations, fixation-time proportions were quantified across predefined areas of interest (AOIs), allowing a descriptive comparison of attention allocation between typographic variants. For the italics variant (Sign 16), 54.3% of total viewing time during the 6.4-s display interval was allocated to the sign area ('Sign_total'), compared with 39.1% for the slash variant (Sign 17). In both cases, the majority of sign-directed viewing time was concentrated on the sign containing the relevant target destination (73.5% and 76.1%, respectively), whereas signs without relevant destinations attracted substantially less attention. At the same time, considerable proportions of fixation time were allocated to the surrounding traffic area ('Traffic_area'; 43.5% and 53.7%), indicating that participants continued monitoring the driving environment while processing the signage information. Percentages across AOIs do not necessarily sum to 100%, as additional fixations may be directed to other areas such as mirrors or the dashboard. These AOI-based proportions should be interpreted descriptively, as the heatmap analysis was intended primarily to illustrate overall attention allocation patterns rather than to provide fine-grained statistical comparisons of fixation density between individual language regions.

Analysis of the time to first fixation (TTFF) on the relevant target further clarified early visual orientation. On motorways, the relevant destination was fixated rapidly in all conditions. Median TTFF values were 691 ms for the baseline sign (Sign 13, $N = 39$, IQR = 516–821 ms), 736 ms for the italics variant (Sign 16, $N = 38$, IQR = 478–882 ms), and 301 ms for the slash variant (Sign 17, $N = 63$, IQR = 130–621 ms). The shorter TTFF for the slash format indicates faster initial detection of the target destination. At the same time, the wider interquartile range observed for the slash condition reflects greater variability in early gaze allocation, suggesting that the compact inline layout facilitated rapid detection but did not consistently guide attention across participants.

On main roads, a comparison of the bilingual variants revealed a similar tendency. The slash variant with right-positioned targets (Sign 4) yielded a median TTFF of 1082 ms ($N = 32$, IQR = 806–1388 ms), whereas the comparable italic variant (Sign 6) showed a

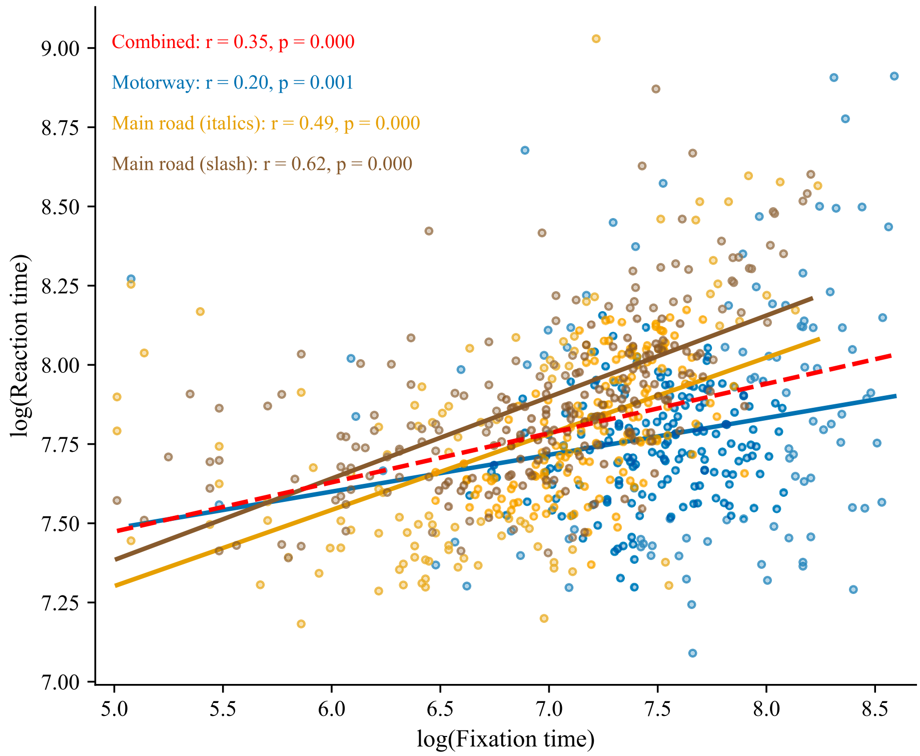


Fig. 11. Pearson correlations between log-transformed fixation times and reaction times, shown separately for motorway and main road signs (italics vs. slash notation), as well as for the combined dataset.

shorter median TTFF of 741 ms ($N = 29$, IQR = 561–992 ms). Across conditions, targets positioned centrally or on the left were fixated earlier than those on the right. This suggests that participants initially directed their gaze towards the central forward field of view and subsequently explored adjacent information, before shifting attention to the right-hand side. This behaviour is consistent with left-to-right scanning patterns and central-field prioritisation reported in previous driving and reading research (Smith & Elias, 2013).

However, shorter initial fixation latencies did not necessarily translate into faster overall reaction times, indicating that early visual detection and subsequent cognitive processing represent partially dissociable stages of sign perception. Design factors such as the number of destinations and the typographic separation of languages appear to influence later processing and decision-making while driving (Zhang, 2021). This dissociation between early detection and semantic processing has also been reported in driving and reading research, where initial fixations reflect attentional capture rather than full information integration (Dambacher & Kliegl, 2007; Rayner, 2009). Taken together, the TTFF results suggest that typographic layout primarily affects early visual orientation, whereas overall performance depends on subsequent cognitive processing.

The correlation analyses further supported these observations by linking gaze behaviour more directly to behavioural responses (see Fig. 11). Across all signs pooled, fixation and reaction times were moderately associated ($r = 0.35$, $p < 0.001$). The scatterplot also revealed considerable dispersion around the regression lines, indicating substantial inter-individual variability in the relationship between fixation duration and behavioural response. Several high-value observations reflected trials with prolonged fixation and reaction times, contributing to the positive correlation while also highlighting variability in processing strategies.

When analysed separately, the relationship was modest on motorways ($r = 0.20$, $p = 0.001$) but substantially stronger on main roads, both for the italics condition ($r = 0.49$, $p < 0.001$) and the slash condition ($r = 0.62$, $p < 0.001$). The steeper slopes observed for the main-road conditions indicate that increases in fixation duration were more strongly associated with delayed behavioural responses under higher information density. By contrast, the flatter motorway slope suggests a weaker coupling between visual inspection time and behavioural response latency under lower information density. Overall, these findings indicate that longer fixations translated more consistently into slower responses when information density was higher, particularly for the slash format.

Comparable to the findings of Rayner (Rayner, 1978; Rayner, 2009), who demonstrated that eye movements provide a sensitive real-time index of cognitive processing across reading and scene perception, our results suggest that fixation durations can serve as indicators of increased processing demands. This interpretation is further supported by evidence showing that longer fixations are systematically associated with greater cognitive load (Dambacher & Kliegl, 2007).

Based on these results, it can be stated that the effects of bilingual signage depend both on the road context and on specific design features. On main roads, the addition of destinations in a minority language was shown to slow processing, and an influence of typographic format was also evident. A comparable pattern emerged in the motorway condition. Slash separation offered certain advantages under motorway conditions but was associated with slower performance on main roads, whereas italics yielded consistently solid results across both contexts.

From a methodological perspective, the combined approach of subjective ratings and objective measures of reaction and fixation times provided a robust framework for assessing cognitive processing demands. The eye-tracking data reliably captured differences in overall sign viewing time, although the more detailed allocation of fixations to the comparatively small destination fields remains challenging and should be interpreted with caution.

Taken together, the findings indicate that italics provide robust performance across contexts, while slash notation can facilitate faster responses on motorways when information density remains low. These results suggest that the effects of typographic design vary depending on information density and road context, consistent with previous findings highlighting the importance of layout simplicity under higher cognitive load (Han et al., 2022; Lyu et al., 2017).

3.4. Implications for practice

The findings offer concrete guidance for the design and implementation of bilingual road signage. They underline that information density is a key determinant of driver performance, as additional destinations substantially increase visual and cognitive demands. Typographic design can be used to optimise legibility under these varying conditions. Italics appear to be a stable and broadly applicable format that consistently improved performance relative to the baseline on both road types, enabling a clear visual separation between language versions without increasing fixation time or disrupting layout balance. These findings support previous recommendations to limit information density and maintain clear typographic differentiation in multilingual signage design (Cai et al., 2024; Zhang, 2021), while extending this work by comparing compact inline bilingual formats and demonstrating context-dependent advantages.

In contrast, the slash notation did not provide an overall advantage and was in several cases associated with longer fixation durations than the baseline. Under motorway conditions, where lower information density and simpler layouts are expected, the slash notation nonetheless produced faster reaction times compared with both the italics and baseline variants. This suggests that its compact visual structure may facilitate rapid target detection even when fixation durations themselves are not reduced.

For practical implementation, these results highlight the importance of harmonising the design of bilingual road signs across all road categories. Establishing a consistent typographic strategy can support readability, information load, and visual clarity, thereby enhancing both safety and equitable linguistic representation in multilingual regions. Italics appear suitable as a standard solution, given their consistently strong performance across contexts, while the specific advantages of slash notation on motorways should also be taken into account to allow for a balance between overall consistency and context-sensitive optimisation.

4. Conclusion

This study examined how different design variants of bilingual road signage affect drivers' information processing and visual attention in a simulated driving environment. The results show that adding destinations in a minority language can increase processing demands and prolong reaction times, with the magnitude depending on typographic format. Italics consistently supported efficient performance, whereas slash separation showed mixed results: it provided advantages on motorways but was associated with slower responses on main roads with higher information density. Fixation times reflected a similar but weaker pattern, highlighting the value of eye-tracking as a complementary measure. Despite these variations, directional choices were almost always correct, indicating that drivers were ultimately able to identify the relevant targets. The key findings include:

- Information density affects processing speed. Adding destinations significantly slowed reaction times on main roads by about 15.9% (GMR = 1.159, 95% CI [1.067–1.258]). When the number of destinations remained constant, differences were markedly smaller, suggesting that cognitive load is primarily driven by overall information quantity, while typographic design modulates but does not fundamentally determine this effect.
- Typographic effects depend on context. On motorways, where information density was constant, the slash format yielded faster reaction times than italics (GMR = 1.131, 95% CI [1.031–1.210]), indicating that its compact structure can facilitate rapid target recognition under simplified layout conditions.
- Eye-tracking results show smaller but consistent differences. Slash variants numerically tended to produce longer fixation durations, suggesting increased visual processing demands, whereas italic variants maintained fixation times comparable to the baseline when information density was constant.
- The simulator-based approach proved effective. Combining subjective ratings with objective performance measures enabled a robust assessment of signage design under controlled yet realistic conditions.

These findings should be interpreted with several considerations in mind. The simulator provided a protected environment without the full complexity of real traffic, as external distractions, interactions with other vehicles, and active driving manoeuvres such as steering or lane changes were absent. Participant responses were recorded via joystick input, capturing reaction tendencies but not full vehicle-control dynamics. Signs were presented as fixed overlays rather than gradually approached roadside objects to ensure consistent legibility and equal viewing conditions across participants. Consequently, the results reflect controlled viewing conditions rather than fully naturalistic driving behaviour. Eye-tracking analyses were limited to sign-level AOIs, which constrained the ability to distinguish gaze behaviour between individual language elements and specific sign components. In addition, the sample primarily consisted of younger participants, which may limit generalisability to the broader driving population.

Despite these constraints, the study provides a solid basis for evaluating alternative design solutions. Future research should test integrated roadside sign presentations, conduct field studies under real traffic conditions, and include broader age groups. In addition, exploring further typographic options beyond italics and slash may identify additional effective strategies. Such work would support the development of consistent guidelines for bilingual signage that balance minority-language visibility with road safety.

CRediT authorship contribution statement

Maximilian David: Writing – review & editing, Writing – original draft, Visualization, Validation, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Dirk Kemper:** Resources, Project administration, Funding acquisition, Conceptualization. **Maximilian Schwalm:** Methodology, Funding acquisition, Data curation, Conceptualization. **Martin Baumann:** Writing – review & editing, Supervision, Methodology, Conceptualization. **Alvaro Garcia-Hernandez:** Writing – review & editing, Writing – original draft, Supervision, Resources, Methodology, Conceptualization.

Declaration of generative AI and AI-assisted technologies in the writing process

During the preparation of this work the author(s) used chatgpt in order to improve the readability and language of the manuscript. After using this tool/service, the author(s) reviewed and edited the content as needed and take(s) full responsibility for the content of the published article.

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.

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throughout the project.

Data availability

Data will be made available on request.

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