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Effect of design factors on drivers' understanding of variable message signs locating traffic events

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ABSTRACT

Background: This article addresses how to combine three elements (a pictogram, an arrow, a city) in a variable message sign (VMS) to locate temporary events (e.g., "congestion before Milan"). We adopted the G1c stack model as a design template, an Advanced Directional Sign (ADS) recommended by the 1968 Convention to locate cities, which can be easily adapted to modern VMS. However, as most of the VMS in operation are not full-matrix, we have also adapted this design to more restrictive display conditions. This adaptation critically concerned the arrow function on the message that either points up broadly (generically, as in G1c) or connects with the city more specifically (explicit). Although G1c reads top-down like a verbal text, previous studies indicated drivers' preference for bottom-up landmark order in VMS, so both ordering criteria were compared in the present study.
Methods: The experiment involved 99 people (70 drivers and 29 drivers in training). Participants were informed that they would see various VMS reporting certain events (e.g., congestion) related to one of four cities along the road. Their task was to identify the event location (before, after the city) after seeing blocks of two consecutive messages (first a complementary message, then the target message), limiting their response to the content of the second message. Three design-focused factors were tested: typographical alignment (left or centre), landmark order (bottom-up or top-down), and arrow function (explicit or generic). The rate of correct location answers was the dependent variable.
Results: Results revealed that comprehension varied greatly depending on the arrow's function and the placing of elements. In the explicit-arrow messages, comprehension was good both in the Top-down and Bottom-up conditions, but in the generic-arrow messages, only in the Bottom-up condition was comprehension good. Likewise, understanding was better in the Before condition than in the After condition in all combinations of Landmark order and Arrow function conditions. In general, left alignment of the central column elements of the VMS improved comprehension respective to centred alignment. Finally, the complementary message factor had an effect under certain circumstances.
Practical implications: The messages displaying a generic arrow (following the G1c model) were better understood when the landmarks were ordered bottom-up, not top-down. In addition, explicit-arrow messages were better understood per se (in the absence of a complementary message) than generic-arrow messages. Overall, this work suggests that improving our

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understanding of how thought processes and design features relate to each other can contribute to safer driving nationally and internationally.

1. Introduction

This article addresses an open question for virtually all traffic operators: how to ensure the comprehension of traffic messages, regardless of the driver's nationality. Clearly, the comprehension of road signs is not always guaranteed (Ishartomo et al., 2020; Shinar & Vogelganz, 2013), and having road signs designed under the same criteria may facilitate comprehension and, consequently, improve road safety. Variable Message Signs (VMS) play an important role in traffic management and road safety by reporting unexpected events and possible solutions in real time (Chatterjee et al., 2002; Chaurand et al., 2015); help divert the flow of traffic (Basso et al., 2021); or contributing to speed reduction (Allmallah et al., 2021; Tay, & de Barros, 2010). Different issues related to format and content have also been explored: the incorporation of text and/or symbols (Shinar & Vogelzang, 2013; Roca, Insa, & Tejero, 2018; Yan & Wu, 2014), the number of information units (Ullman et al., 2005; Babić et al., 2020) or the content of the message (Chatterjee et al., 2002; Zhao et al., 2019). In an increasingly globalized and mobile world, this work aims to improve our understanding of complex VMS configurations. In 1968, the Convention on Road Signs and Signals (UNECE, 2006) standardized the signing system for road traffic (road signs, traffic lights, and road markings) to be used internationally, and today, 69 countries have already ratified it (UNECE, 2022). However, despite harmonization efforts, it is still possible to design road signs following the 1968 Convention but with different models. For example, to locate cities on the route on Advance Directional Signs (ADS), two alternative models can be used: the stack model G1c (Fig. 1-C) or the diagram models G1a and G1b (Fig. 1-A/B). However, having different models of road signs may confuse drivers and, consequently, make it difficult to understand them as they must be interpreted differently.

Although the psychological impact of road signs on drivers has been extensively researched, more emphasis has traditionally been placed on the attentional and perceptual aspects (Castro & Horberry, 2004) than on their understanding (Cristea & Delhomme, 2014; Reinolsmann et al., 2019; Shalloe et al., 2014). Research on understanding complex traffic signs (see Lucas-Alba et al., 2011; Shinar & Vogelzang, 2013) has shown that drivers easily recognize road signs, or at least some of their parts (e.g., warning for wind, congestion, or road works) because these are known elements stored in long-term memory (Crundall & Underwood, 2001). However, understanding does not occur solely at the expense of an automatic passive process through the simple retrieval of information from long-term memory. For instance, placing drivers in front of a road sign that combines known elements unprecedentedly will make them particularly aware of that combination. A proper comprehension may then require complex processing of the elements that configure the traffic sign (Castro et al., 2008; Vargas et al., 2011). Applied research allows us to explore which designs and configurations are most functional in terms of comprehension and advance our understanding of how drivers process this information and obtain the meaning of signs. In this study, we will apply this type of research by focusing on how to adapt ADS to VMS.

1.1. *The case study: Qualitative location in VMS*

VMS are common devices on the European road network that combine a pictogram and alphanumeric text. Drivers find the information provided in the international alphanumeric text more difficult to understand. In the case under study, there are mainly three types of information provided in alphanumeric text: the name of the city/cities, the distance to an event measured in kilometers or miles, and the location of the event ahead expressed through prepositions (such as "after" or "before"). While the name of the city/cities may not be a problem (drivers only have to identify them), the other two types of text may be hard to understand. Regarding the distance to an event, some drivers may have doubts about the type of unit (kilometers or miles) to which it refers in this or that country. In addition to that, even if drivers could manage both types of units, there are reasons for not using numbers in the text (Arbaiza and Lucas-Alba, 2012). VMS are designed to inform of an event (such as wind, congestion or road works) that are volatile because their localization can change, spread along the road, or disappear. In addition, the operators of the Traffic Management Centers may encounter some difficulties, due to technical issues (updating information in real time) and legal issues (responsibility for the information transmitted, especially if it is very specific). This practical context is what has led us to give priority to the analysis of qualitative

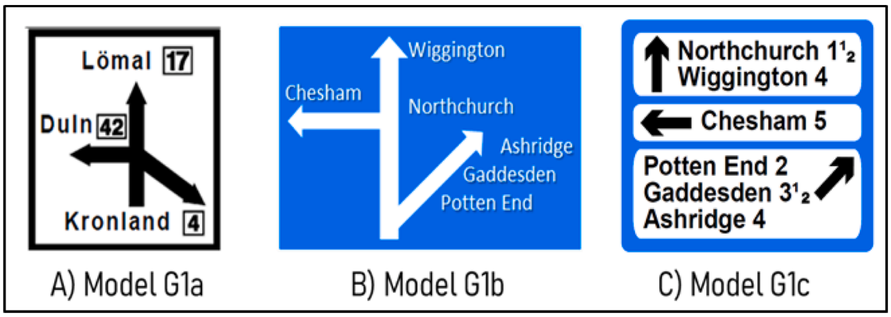

Fig. 1. Advanced directional signs models G1 a/b/c (UNECE, 2006).

Fig. 2. Example of a VMS with two columns; one for pictogram and one for alphanumeric text (from Nouvier et al., 2009).

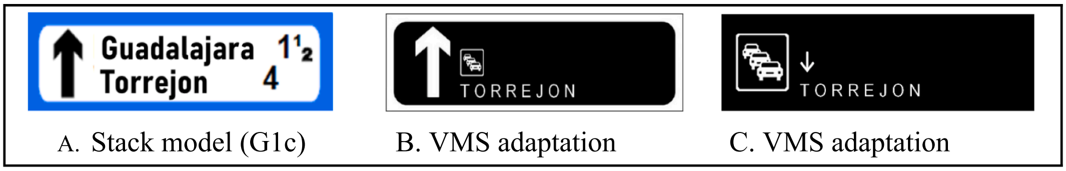

Fig. 3. Transformation from the original stack model (A) to the VMS (B and C).

location on VMS.

The third type of information refers to the event's location in space expressed through prepositions. Prepositions in the VMS are written in the language of the country (Italian, French, Swedish, etc.), which is an insurmountable obstacle for drivers who do not know that language. Consequently, avoiding alphanumeric text (except for the name of the city/cities) may facilitate comprehension for any international driver. This could be achieved by eliminating information on the distance to the event, and focusing on the location of the event qualitatively without using any prepositions. Prepositions can be substituted by symbols (Nouvier et al., 2009), and arrows are the most obvious choice. Arrows appear in a diversity of diagrams such as flowcharts, illustrations, guideboards, route maps, or road signs (Di Stasi et al., 2012). Arrows are "meaningful graphic forms" that encourage people to interpret causal and functional aspects in a diagram (Tversky, 2005; Tversky et al., 2000). They can capture a great variety of semantics with their simple form, which makes them powerful resources for communicating spatial knowledge in a static diagram (Kurata & Egenhofer, 2005).

Clearly, the contextual versatility of arrows is both a strength and a weakness. Instead of being automatically recalled from long-term memory (as with words, Carroll, 2008), the dozens of possible arrow meanings (Horn, 1998) are inferred on the fly from their immediate visual context, forming an "arrow diagram" (Kurata & Egenhofer, 2005). This configuration would act as a unit of information so that drivers must consider the arrangement of the components and the possible relations among them to interpret its meaning (Kurata & Egenhofer, 2008). In addition, Di Stasi et al. (2012) pointed out that the congruence in the orientation of graphic elements included in traffic signs facilitates comprehension.

1.2. *Design alternatives: Stacks vs diagrams*

To sum up, it is reasonable to expect that a VMS that only includes a pictogram, a city name, and an arrow could be more internationally understood because it avoids cultural and linguistic barriers (such as measurement of distance or words in some language). These three elements —pictogram, arrow, city— can be configured in a VMS in several ways. The present study aimed to assess different combinations to determine which one may lead to the best understanding of the information displayed on a VMS. Among the different alternatives, we decided to test VMS messages based on the stack model. There are several reasons in favor of this alternative. The stack model G1c is an ADS that is already used to locate fixed points such as cities (see Fig. 1C), and it can be easily adapted to a VMS.

It is worth noting that the VMS infrastructure imposes certain design limitations, which depend on the type of VMS. We shall focus on a full matrix VMS divided into columns: one for the pictogram (on the left side) and the other one for the alphanumeric text (on the right side; see Fig. 2). Although initially, the purpose of an alphanumeric text column is to display text and numbers (Ellenberg & Fabre, 1995), modern VMSs use advanced technology (more LEDs, smaller pixel distances) that makes it possible to show not only symbols (like arrows) but also small traffic signs (Nouvier et al., 2009; Haitz & Tsao, 2011). We are designing VMSs assuming that this technology is available.

Fig. 3A offers an example of a road sign that follows the stack model (G1c). One possible adaptation of G1c to a VMS is to include the arrow on the pictogram column and a small traffic sign stacked over the city name on the alphanumeric text column (Fig. 3B). Another possible composition is to include the traffic sign on the pictogram column and an arrow stacked over the city name on the alphanumeric text column (Fig. 3C).

With these two compositions as starting points, we have modified several design characteristics to determine which arrangements are better understood. Specifically, we tested the effect of the elements' order on the alphanumeric text column. Message comprehension could change depending on how the panel's elements are placed. The original stack model ordered the elements from top to bottom, following the linguistic inertia (left-right, top-down; Bergen & Chan, 2005; Spalek & Hammad, 2005). However, these traffic signs also allow ordering elements from bottom to top, like a map or a diagram. Previous studies (Hernando et al., 2022) showed that configurations based on the horizontal axis (i.e., the arrow pointing to the right next to the city name) are not adequately understood

Fig. 4. VMS adaptations following a bottom-up order of the elements (left-alignment).

Fig. 5. Centred-element VMS designs.

compared to the vertical axis. Therefore, the elements' order was only manipulated with respect to the vertical arrangement.

In real life, drivers are exposed to different types of traffic signs, and they may be familiar with the route on which they are driving. These are factors that may also affect the comprehension of traffic messages. This work also explored the possible influence of these factors. More specifically, on the one hand, we tested to determine whether previous presentation of one of the compositions of the VMS affects the comprehension of the other composition. On the other hand, we investigated the influence of route knowledge on VMS comprehension.

Finally, different typographic alignments of the text can be used in VMSs. Occasionally the elements on the alphanumeric are justified to the left, like the original stack model (Fig. 3A). But sometimes, a VMS shows messages centred on the alphanumeric column (Fig. 2). This factor was also studied in this work (for a synoptic of the entire process see Appendix A).

2. Method

2.1. Participants

The experiment involved 99 people (52 women) whose mean age was 26.9 years ($SD = 8.20$; min = 18.0; max = 58.0). Participants between 18 and 25 years of age constitute the largest group (60.6 %), followed by the group of 26 to 35 years of age (26.3 %), that of 36 to 45 years of age (8.1 %), the group of 46 to 55 years old (4.0 %) and over 55 years old (1 %). Seventy-two had a driving license, and twenty-seven had passed the theoretical exam. Regarding driving experience, 29 had no experience, 31 had been driving for<5 years, 29 had driven between 6 and 15 years, and 10 for>15 years. Planned comparisons between drivers and drivers in training showed no significant differences in comprehension overall. The sample presented a medium–high educational level (67 % were university graduates, 17 % had professional training, 8 % were high school graduates, and 8 % had basic education).

2.2. Design

On the one hand, three variables related to the format and design of VMSs were manipulated. Firstly, *arrow function (generic/explicit):* the first design incorporates the event pictogram in the alphanumeric column, leaving the up-arrow on the left side (Fig. 3B); whereas the second design relocates the event pictogram on the left side, and a small arrow is placed with the city names on the alphanumeric column (Fig. 3C). Also, *landmark order (top-down/bottom-up):* top-down placement of elements follows a stacked order. For example, if we want to inform that there is a traffic jam before Torrejon, we would place the pictogram in one row, and below it, the city name (Fig. 3B). Bottom-up placement orders the elements like a map, following a diagrammatic strategy. Thus, the element on the bottom is the nearest, that is, the first one on my route (Fig. 4, left).

The third variable is the *typographic alignment (left-centre)*, and two options were considered: justifying the elements on the alphanumeric part to the left as in the stack model (Fig. 4), or placing them on the centre of the alphanumeric part (Fig. 5).

Three more variables were considered. One of them is *event location (before/after)*. An event can be located (1) before a landmark, (2) after a landmark, or (3) between two landmarks. This work focuses on the before/after cases, which include one landmark (city) on the VMS. All the signaling in ADS is oriented to road sections that end at a fixed point in the network (usually, a city), so for drivers, 'before' is the standard case (see Hernando et al., 2022).

Besides the VMS message design, prior knowledge and information from the context may also influence drivers' comprehension. If a traffic message is clear, the information it displays should be enough to understand where the event takes place. However, if it is not clear enough, having prior information about the route can help understand it. Furthermore, currently, drivers can find themselves having to pay attention to different formats of traffic signs (e.g., fixed, variable, onboard). If drivers were given different layouts concerning the same event locations, what synergy would there be between them? To answer this question, the variable *complementary message (present/absent)* was also included in the experimental design.

Correct answers were considered as the dependent variable. Table 1 shows the design of the empirical study using centred element signs; the same template was used with left-justified element messages (see Appendix B). We analyzed comprehension rates as the

Table 1
Experimental design using centred signs.

Location	Complementary message		Arrow function	Landmark order	Target message
Before	Present		Explicit	Top-down	
				Bottom-up	
			Generic	Top-down	
				Bottom-up	
	Absent	+	Explicit	Top-down	
		+		Bottom-up	
		+	Generic	Top-down	
		+		Bottom-up	
After	Present		Explicit	Top-down	
				Bottom-up	
			Generic	Top-down	
				Bottom-up	
	Absent	+	Explicit	Top-down	
		+		Bottom-up	
		+	Generic	Top-down	
		+		Bottom-up	

mean of correct answers per participant and condition.

2.3. Stimuli

We used the MediaLab Software (v. 2014) to present the stimuli and record the responses. The traffic signals displayed occupied an area of 1024x290 pixels. The adopted VMS template (a 174x174-pixel pictogram plus a 60x70-pixel arrow; Arial size 40 text) and G1c template (a 100x174-pixel arrow plus an 80x80-pixel pictogram; Arial size 40 text) are shown in Fig. 3. All city names shown consisted of three syllables, and the pictograms were well-known (Lucas-Alba et al., 2011).

2.4. Procedure

Recruitment took place by direct invitation to students at a local driving school and with billboards on the University Campus. Participants were asked to read and sign an informed consent and answer some sociodemographic and driving-related questions. We evaluated the participants individually, sitting 60 cm away from a computer with a 22-inch screen, in a private room of a driving school or the faculty.We then asked the participants to imagine driving on the A2 highway, leaving Guadalajara, going towards Getafe, and passing through three cities (Alcalá, Torrejón, and Coslada). Participants were randomly assigned to one of two groups (Route listing Group and Non-route listing Group). Participants in the Route listing Group were requested to sort the name of the cities in order of appearance when following the previously mentioned route. This condition was meant to consolidate the memory of the order of appearance of the cities on the route. Participants in the Non-route listing Group did not undergo this experimental condition.

Subsequently, the computer showed 24 message blocks, 16 of which were explicitly before/after messages (Event Location), top-down/bottom-up messages (Landmark order), and an explicit/generic approach (Arrow function). Half of the sample were shown the left-justified messages and the other half the centred messages (Typographic alignment). We requested all participants to decide as quickly and as accurately as possible. The instructions indicated that they would see two consecutive messages, and then, they would be asked where the event was located. The written instructions specified that they would have two options (e.g., "*1. Before Coslada*" and "*2. After Coslada*"), whose position was counterbalanced; and then, they should press the corresponding key on the keyboard (Keyboards 1 and 2). Finally, they were instructed to always respond according to the second message. After reading the instructions, the participants performed a block of 3 practice trials followed by 24 randomized experimental trials. In the control blocks, the complementary message was replaced by a neutral stimulus (a cross). All stimuli were placed in the centre of the screen. The order of presentation was as follows: fixation cross (500 ms), complementary message or neutral stimuli (2 s), fixation cross (500 ms), message tested (4 s). Between each trial, the screen was black for 3 s. The complete session lasted approximately 20 min.

3. Results

Statistical analyses were performed with IBM SPSS v.26 software. Analysis of variance was performed to examine the effects of Route listing (Present or Absent), Typographic alignment (Centred or Left justified), Complementary message (Present or Absent), Landmark order (Top-down or Bottom-up), Arrow function (Generic or Explicit), and Event location (Before or After). Typographic alignment and Route listing were between-subject factors, whereas the rest were within-subject factors.

Neither the main effect of Route listing nor its interactions had a significant effect; $F(1, 96) = 2.137$, $p = 0.147$, $\eta_p^2 = 0.022$, for the main effect of Route listing; $F(1, 96) = 1.585$, $p = 0.211$, $\eta_p^2 = 0.016$, for the interaction between Route listing and Event location; $F(1, 96) = 1.441$, $p = 0.263$, $\eta_p^2 = 0.015$, for the interaction between Route listing, Landmark order, Arrow function and Event location; and $Fs < 1$ for the remaining interactions. Therefore, Route listing did not have any effect over correct answer rates.

Typographic alignment significantly interacted with Landmark order, $F(1, 96) = 12.158$, $p < 0.005$, $\eta_p^2 = 0.112$; and with Arrow function, $F(1, 96) = 6.482$, $p < 0.05$, $\eta_p^2 = 0.063$. The interaction between Typographic alignment, Landmark order, and Arrow function was borderline, $F(1, 96) = 3.909$, $p = 0.051$, $\eta_p^2 = 0.039$. This interaction (Fig. 6) was explored through a simple effect analysis that contrasts correct answer rates when elements were centred compared to when they were left justified, fixing the rest of the conditions to be constant. Results indicated that when the Landmark order was bottom-up, correct answer rates were significantly higher in Left justified condition than in the Centred condition, either when the arrow function was explicit or generic, $ps < 0.01$. In contrast, when the Landmark order was Top-down, correct answer rates were significantly lower in the Left justified condition than in the Centred condition when the arrow function was generic, $p < 0.01$, and nonsignificant when the arrow function was explicit, $p > 0.05$.

The interaction between Typographic alignment, Landmark order, and Event location was also borderline, $F(1, 96) = 2.922$, $p = 0.087$, $\eta_p^2 = 0.030$. This interaction (Fig. 7) was examined by means of a simple effect analysis, which contrasts correct answer rates when elements were centred compared to when they were left justified, fixing the rest of the conditions to be constant. Results revealed that the Left justified condition did not differ from the Centred condition, $ps > 0.05$, except when the landmark order was bottom-up, and the event location was placed after, $p < 0.01$.

There was a significant effect of Landmark order, $F(1, 96) = 68.537$, $p < 0.001$, $\eta_p^2 = 0.417$; Arrow function, $F(1, 96) = 33.270$, $p < 0.001$, $\eta_p^2 = 0.257$; and of Event location, $F(1, 96) = 31.206$, $p < 0.001$, $\eta_p^2 = 0.245$. Arrow function significantly interacted with Landmark order, $F(1, 96) = 9.522$, $p < 0.005$, $\eta_p^2 = 0.090$, as well as with Complementary message, $F(1, 96) = 9.931$, $p < 0.005$, $\eta_p^2 = 0.094$. The interaction between Landmark order and Complementary message was borderline, $F(1, 96) = 3.667$, $p = 0.058$, $\eta_p^2 = 0.037$. Finally, the interaction between Landmark order, Arrow function, Complementary message, and Event location was significant, $F(1, 96) = 5.985$, $p < 0.05$, $\eta_p^2 = 0.059$. This four-variable interaction involved all the significant main effects and interactions, except for the main effect of Typographic alignment and its previously analyzed interactions. The remaining effects did not have a significant effect,

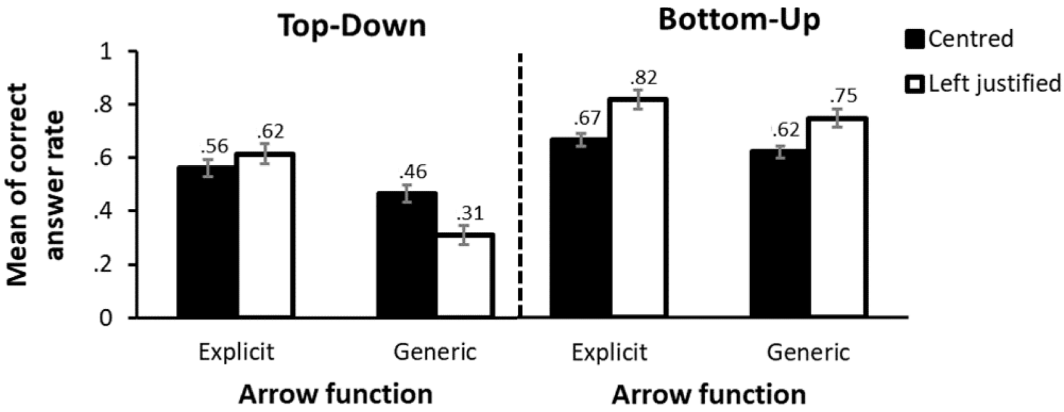

Fig. 6. Mean of correct answer rates for the interaction between typographic alignment, landmark order, and arrow function.

$F_{max} = 1.948$. Consequently, this interaction was explored more deeply. To understand the reason for this interaction, results were plotted in Fig. 8, which illustrates the pattern of results of each combination of Landmark order and Arrow function conditions, as a function of Complementary message and Event location.

An examination of Fig. 8 reveals that the pattern of results seems to be similar for all combinations of Landmark order and Arrow function conditions (i.e., Top-down & Explicit, Top-down & Generic, Bottom-up & Explicit, and Bottom-up & Generic conditions). Thus, it can be seen from this figure that, in general, correct answer rates are higher in the Before condition than in the After condition. Furthermore, it is clear from this figure that correct answer rates are lower in the Top-down & Generic combination than in the rest of the combinations. Also, in the Bottom-up & Explicit and Bottom-up & Generic combinations, correct answer rates seem higher than in the remaining combinations. Lastly, it appears that the complementary message had some effect in some combinations under the same condition of event location (Before or After).

To test these impressions statistically, we performed analyses of simple main effects. To compare correct answer rates among all the combinations of Landmark order and Arrow function conditions, these two variables were transformed into one variable with four levels, where each level of the variable is a combination of the two variables. After this transformation, we conducted a simple effect analysis to compare the Before and After conditions fixing the rest of the conditions to be constant. Simple main effects analysis showed that correct answer rates were higher in the Before condition than in the After condition in all combinations of Landmark order and Arrow function conditions, $ps < 0.05$. The Top-down & Generic combination was an exception, as the difference between the Before and After conditions was nonsignificant when a Complementary message was present, $p = 0.15$.

Subsequently, we performed a simple effect analysis to compare the effect of providing participants with the complementary message. The analysis showed that correct answer rates were lower in the Top-down & Explicit combination in the After condition when the complementary message was present than when it was absent, with the opposite results in the Top-down & Generic combination $ps < 0.05$. Furthermore, regarding the Bottom-up & Explicit combination, correct answer rates were lower in the Before condition when the complementary message was present than when it was absent $p < 0.05$. Finally, in the Bottom-up & Generic condition, the complementary message had no effect, $ps > 0.05$.

Next, we carried out several simple effect analyses to compare correct answer rates among different combinations of Landmark order and Arrow function conditions. In the Top-down & Generic combination, correct answer rates were significantly lower than in the remaining combinations, under each combination of Complementary message and Event location. An exception was when we compared the Top-down & Generic combination with the Top-down & Explicit combination. In these combinations, the correct answer rates were not significantly different when the complementary message was present, and the event location was placed after, $p > 0.05$. Moreover, correct answer rates were significantly higher in the Bottom-up & Explicit combination than in the Top-down & Explicit combination, $ps < 0.005$. Exceptions were when the complementary message was present and the event location was placed before, and when the complementary message was absent, and the event location was placed after. In the former case, the difference was nonsignificant, $p > 0.05$, and in the latter, it was borderline, $p = 0.075$.

In contrast, correct answer rates were not significantly different in the Bottom-up & Explicit combination than in the Bottom-up & Generic combination, $ps > 0.05$. An exception was when the complementary message was absent, and the event location was placed before, as this difference did reach statistical reliability, $p < 0.01$. Similarly, correct answer rates between the Bottom-up & Generic combination and the Top-down & Explicit combination were not significantly different, $ps > 0.05$. An exception was when the complementary message was present, and the event location was placed after, as, in this case, the correct answer rates were significant, $p < 0.05$.

An examination of Fig. 8 shows that the highest correct answer rates correspond to the Bottom-up & Explicit combination when the complementary message is absent, and the event location is located before, whereas the lowest correspond to the Top-down & Generic combination when the complementary message is absent, and the event location is located after. To assess whether the conditions with the highest and lowest numerically correct answer rates were significantly different from the other conditions, the four variables were transformed into one variable with sixteen levels, where each level of the variable is a combination of all four variables. Then, we

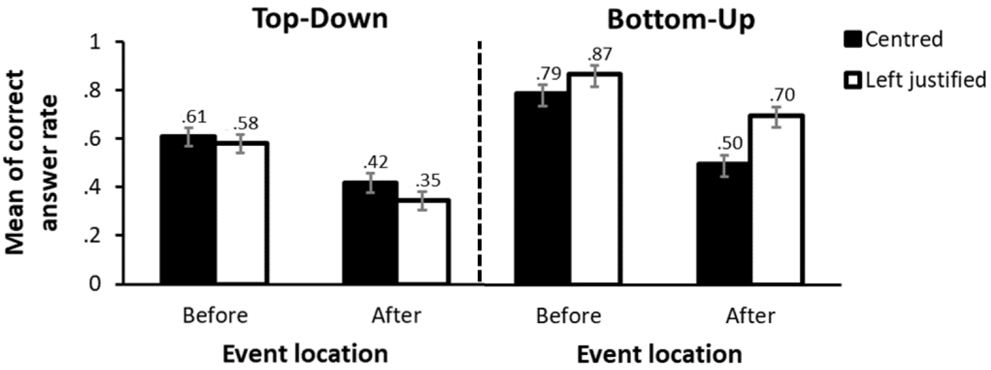

Fig. 7. Mean of correct answer rates for the interaction between typographic alignment, landmark order, and event location.

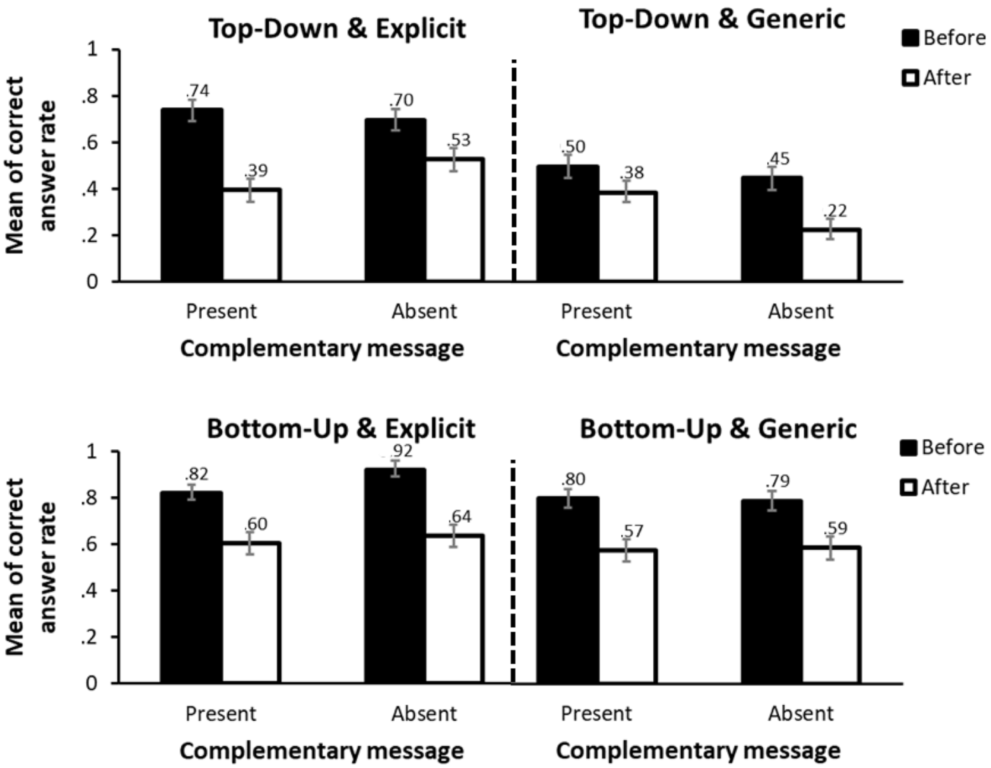

Fig. 8. Mean of correct answer rates for the interaction between landmark order, arrow function, complementary message, and event location.

carried out a simple effect analysis to compare all the conditions. Results confirmed that both the highest and lowest correct answer rates were significantly different from the other conditions, $ps < 0.05$.

4. Discussion

The main target of this work was to assess the understanding of the information displayed by different designs of VMS (adapted from the stack model of ADS) consisting of three elements: a pictogram, a city name, and an arrow. The main design factors were the function assigned to the arrow (explicit or generic), the landmark order (bottom-top or top-down), and the type of event location (before or after) with respect to a city. Results revealed that understanding highly varied depending on the arrow's function and the placement of the elements. More concretely, the Top-down and Generic-arrow combination led to a much worse comprehension than the other combinations. Thus, when the arrow had an explicit function, understanding was good, independently of the placement of elements. On the contrary, when the arrow had a generic function, the signal was only well understood if the elements were placed bottom-up, but not if they were placed top-down.

In explicit-arrow messages, the arrow is placed above or below the city name and can take two directions: pointing up or down. In this type of messages, comprehension was good because the arrow can take on two roles: a) it represents the event, and b) it places the event relative to the city. Thus, when the head of the arrow is close to the city name, the arrow indicates that the event occurs before the city, whereas when the tail of the arrow is close to the city name, the arrow informs that the event occurs after the city.

In generic-arrow messages, the event is placed above or below the city name, and the arrow is placed on the left side of the sign and can only take one direction: pointing up. In such messages, the arrow can be interpreted in two ways. If drivers assume that the arrow is part of a stacked ADS type, it will be interpreted as a deictic expression ("to there"), and the centre column will be read as a verbal list: the first thing you read (at the top) is the closest. If, on the contrary, drivers assume the arrow is part of a diagrammatic ADS type, it will be interpreted as a road icon with which the event and the city are aligned: what is below is closer, and what is above is further away. In view that comprehension was good for this type of signals when the items had to be read bottom-up, but poor when the items had to be read top-down, our results suggest that drivers interpret the arrow diagrammatically. This result is interesting because the stack ADS (not diagrams) is standard in our participants' country (BOE, 2014).

The diagrammatic interpretation of generic-arrow messages explains well why understanding was much better in the bottom-up messages than in the top-down messages, but not why this also happens in the explicit-arrow messages. A possible explanation is that, although in the explicit-arrow messages, the arrow clearly informs the localization of the event with respect to the city, drivers may have a general tendency to read signals bottom-up (i.e., adopting a relative frame of reference, Levinson, 2003; Hernando et al., 2022), which could favor the correct understanding of the message. Another possible explanation involves the concept of *arrow diagram* that Kurata and Egenhofer (2008) consider a syntactic unit: bringing components closer to the arrow makes it easier to visualize a unit as such.

Interestingly, the better comprehension of explicit-arrow messages over generic-arrow messages was corroborated by the effects found with the complementary message factor. Thus, on the one hand, the previous presentation of generic-arrow messages reduced comprehension of explicit-arrow messages compared to the absence of the complementary message. This agrees with the idea that generic-arrow messages are misunderstood; presenting a message that was not clearly understood would obscure the comprehension of a message that would be easily understood. On the other hand, the previous presentation of explicit-arrow messages improved the comprehension of generic-arrow messages. This result corroborates the idea that explicit-arrow messages are well understood per se; presenting a well-understood message would increase comprehension compared to a message presented alone.

Another relevant finding of the present study is that understanding was better in the Before condition than in the After condition in all combinations of Landmark order and Arrow function conditions. This result extends the work of Hernando et al. (2022) and, taking all the results together, confirms that (as opposed to the top-down or left-right messages) the bottom-up order is the most functional for locating events before a city. Likewise, this result is consistent with classical experiments (Ehrlich & Johnson-Laird, 1982; Mani & Johnson-Laird, 1982) that have demonstrated the difficulty of comprehending messages that lead to indeterminate locations. Given that the landmark order (Top-down or Bottom-up conditions) was counterbalanced for both Before and After conditions in the present study, this finding cannot be accounted for by drivers' tendency to read signs bottom-up. One possible reason for the poor results for the After condition is that, as drivers are usually informed through traffic panels of approaching cities, they automatically may infer that the event is located before the signaled city, independently of the information provided by the arrow. Faced with After messages, drivers may infer that the arrow represents a transition (movement) but also a logical relationship (e.g., driver-destination; see Kurata & Egenhofer, 2008), concluding that the event is Before the city. An alternative explanation stems from the difficulty of reconstructing the preferred mental model when the event is located After the city (referent object) compared to Before the city (see Ragni & Knauff, 2013; Hernando et al., 2022).

These mechanisms mentioned to explain the results could function concurrently, so each mechanism may have an additive effect over the total effect. In fact, results showed that the experimental condition with all these mechanisms in its favor (where the sign had to be read bottom-up, the arrow was explicit, the event location was located before, and no generic-message was displayed before) achieved the highest comprehension. Conversely, the experimental condition that had all these mechanisms against it (where the sign had to be read top-down, the arrow was generic, the event location was located after, and no explicit-message was displayed before) achieved the lowest comprehension.

Another finding of this work is that the typographic alignment of the elements of the central column of the VMS to the left affects comprehension under certain circumstances. In general, it seems that justifying elements to the left of the pictogram promotes a bottom-up reading of the generic-arrow. This is because when elements are left-justified, understanding of the generic arrow is better when assuming a bottom-up order, but when elements are centred, understanding of the message is better when reading top-down. As aligning elements to the left brings the elements closer to the arrow, this may favor taking the arrow as a road icon, reinforcing the diagrammatic interpretation of the arrow. Unfortunately, this explanation does not predict all the results found with the typographic alignment. For instance, it does not explain why left justification also improved understanding in explicit-arrow messages that must be read bottom-up. Nor does it explain why left justification facilitated comprehension in the After condition in bottom-up messages. Consequently, the role played by the justification of the elements is not yet well understood, and more research is required in this regard. However, there are some promising avenues such as the driver's preference for a relative reference frame (Levinson, 2003), the formalization of alternative interpretations for arrow diagrams (Kurata & Egenhofer 2005; 2008), or drivers' likely preference for a temporal order of the sequence from behind (past) to front (future) (Fuhrman & Boroditsky, 2010; Rinaldi et al., 2018; see also Hernando et al., 2022).

4.1. Some practical implications

Messages presented in the VMS included the names of four cities along a route in Madrid. The present study investigated whether

Fig. 9. Directional signs on motorways, primary, and local routes (Department for Transport, 2013).

knowing the route may affect VMS comprehension. For this purpose, some participants had to order the cities correctly before being asked about the VMS. Other participants did not have to complete this task. There was no evidence in the study that this task influenced comprehension of the VMS. However, given that the study did not include a test to confirm whether the task improved knowledge of the route or whether knowledge of the route was better in participants who had to do the task than those who did not, this result needs to be taken with caution.

In conclusion, our findings support the idea that it is possible to inform international drivers of road events qualitatively, with a high level of understanding, by locating the event with respect to a city. To ensure a good comprehension of the message, it is best to design a VMS where elements on the alphanumeric are left justified, are read bottom-up, the arrow is explicit, and the event is located before the city. It is also possible to obtain a good comprehension of messages when the arrow is generic, as long as the elements are ordered bottom-up.

These results have an important implication for designing VMS and ADS in general. First of all, VMS design factors have a considerable effect on the understanding of the displayed messages and, therefore, on its effectiveness in road traffic management and safety (Shinar & Vogelzang, 2013). Our findings support that both format (eg, arrow feature, typographical alignment, or landmark order) and content (eg, event location) should be considered when designing effective messages (Castro et al., 2008; Roca et al., 2018; Zhao et al., 2019). Second, there are practical implications related to the current recommendations. On the one hand, in the 1968 Convention, a stacked ADS (G1c; see Fig. 1C) was adopted where city names are read top-down; the higher the city is located on the signal, the closer it is to the driver. It is reasonable to assume that in such ADS, correct understanding depends critically on the distance (in kilometers or miles) displayed. For example, the British Department for Transport (2013) recommends ordering the approaching cities top-down when there is no arrow on the board. However, contravening the 1968 Convention, when the sign incorporates an arrow pointing up, their recommendation is to order cities bottom-up and align their names to the left (see Fig. 9). Considering the results of our study, it is likely that drivers understand this second alternative better. If future research verifies our results, the agreements adopted in the 1968 Convention on stacked ADS could be reviewed.

4.2. Limitations of the study

As in any study, the present study has its strengths and weaknesses. Regarding its strengths, this study was not limited to examining which VMS designs obtained better comprehension, but it also explored the possible underlying mechanisms by which drivers interpret directional messages. Regarding the weaknesses, the sample was composed of young drivers of a single nationality (Spaniards), which limits our results. Taking into account data from the national census (DGT, 2020), further research should also evaluate the generality of our results by including more male drivers (the female sample is slightly overrepresented in our study), but especially incorporating older drivers (from 35 years and over) and with more years of driving experience (>5 years). It would also be interesting to include drivers with different nationalities (accustomed to different types of signaling based on batteries, diagrams or both). One possibility is to analyze the impact of certain variables (age, driving experience, educational level) on message comprehension. Our starting point is also improvable. Along the lines of supranational organizations such as the UN, our focus has been on universalizable traffic messages (see also Nakamura and Zheng-Treitler, 2012). However, we do not provide evidence on whether comprehension of these messages would be better than comprehension of text messages in the national context (Shinar and Vogelzang, 2013), or whether text messages involve more cognitive effort than text messages (e.g., require a longer processing time; Roca, Insa and Tejero, 2018). Another aspect to take into account is what specific event (here, congestion) is located with respect to a city. Previous studies with drivers from different countries showed that certain pictograms (congestion, road works, wind, snow) present high and very similar comprehension rates (above 89 %, Lucas-Alba et al., 2011), and also that showing these pictograms with explicit arrow messages did not influence the observed comprehension rates (Hernando et al., 2022). However, checking whether other untested pictograms (e.g., accident, closed road) affect the understanding of the messages in this study is a pending task. In addition, future studies should also go a step beyond desktop experiments and test the understanding of these traffic messages while driving, as it is a complex activity that also consumes cognitive resources. Driving simulator experiments would be the next step, collecting data on drivers' behavior and how understanding complex messages affects their performance and vice versa. Further research should also test untrained people to determine whether the mechanisms proposed in this study to interpret the directional signs are learnt by drivers during their training in traffic rules and signs or, in contrast, they are general mechanisms that people use to obtain the meaning of diagrammatic information.

CRediT authorship contribution statement

Ana Hernando: Conceptualization, Software, Methodology, Formal analysis, Investigation. **Antonio Lucas-Alba:** Conceptualization, Methodology, Formal analysis, Writing – review & editing, Funding acquisition. **Maria Teresa Blanch:** Writing – review & editing, Investigation, Supervision. **Andrés Sebastián Lombas:** Conceptualization, Methodology, Data curation, Writing – original draft, Formal analysis.

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.

Data availability

Data will be made available on request.

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Appendix A

See Fig. 10.

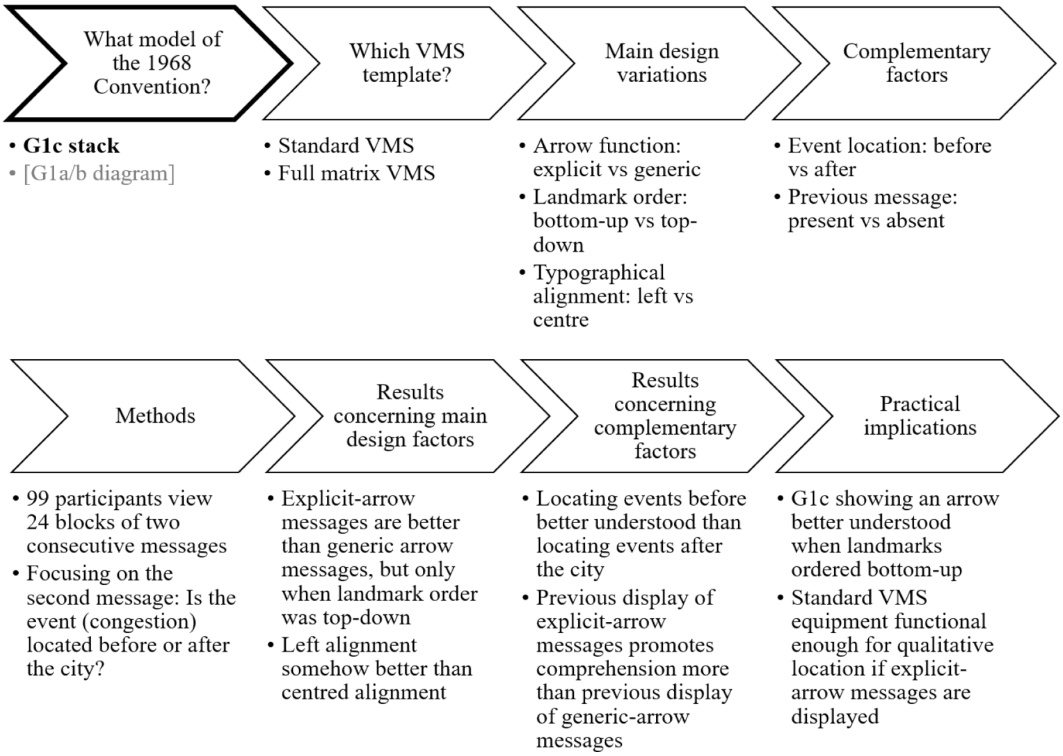
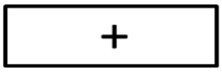
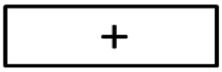
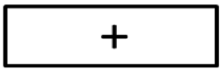
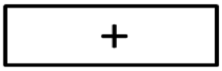
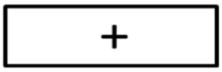
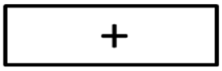
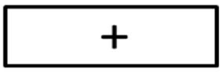
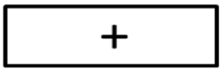


Fig. 10. Finding the most understandable combination of three elements (pictogram, arrow, city).

Appendix B

See Table 2.

Table 2
Experimental design using left-justified signs.

Location	Complementary message		Arrow function	Landmark order	Target message
Before	Present		Explicit	Top-down	
				Bottom-up	
			Generic	Top-down	
				Bottom-up	
	Absent		Explicit	Top-down	
				Bottom-up	
			Generic	Top-down	
				Bottom-up	
After	Present		Explicit	Top-down	
				Bottom-up	
			Generic	Top-down	
				Bottom-up	
	Absent		Explicit	Top-down	
				Bottom-up	
			Generic	Top-down	
				Bottom-up	

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